Search for Low-Mass WIMPs with **SuperCDMS**

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Fermilab Center for Particle Astrophysics
Joint Experimental-Theoretical Physics Seminar
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The dark matter problem

An 80-year old puzzle
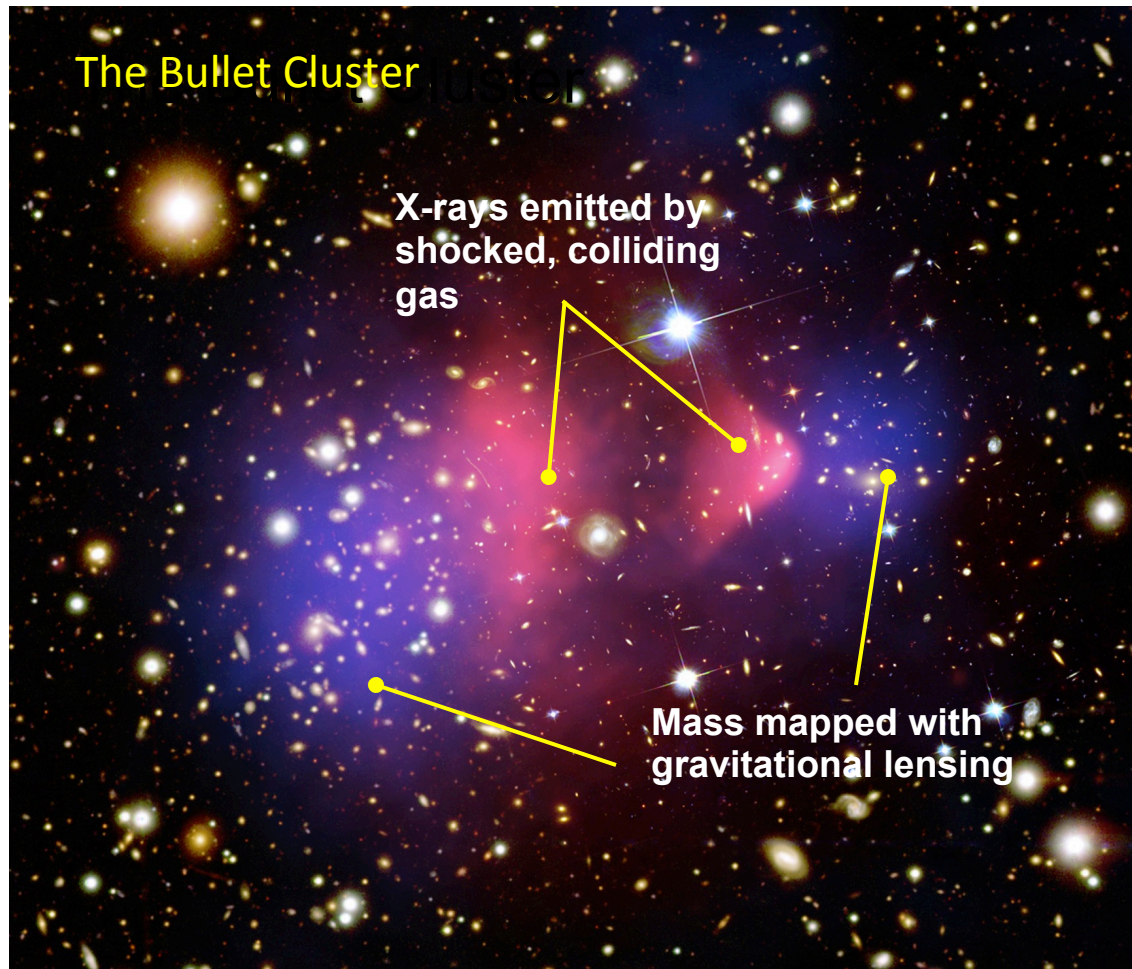

Coma Galaxy Cluster
(SDSS)

In 1933:

Fritz Zwicky analyzed velocity dispersion in Coma Cluster

Individual galaxies move too fast for a bound system…

Posited existence of unseen matter in the cluster and named it "dark matter"

The Modern View of Dark Matter

The Bullet Cluster

X-rays emitted by shocked, colliding gas

Mass mapped with gravitational lensing

What we know:
It's stable, cold, gravitationally interacting, non-baryonic, interacts little with itself (or not at all), composes ~80% of matter in the Universe…

But:
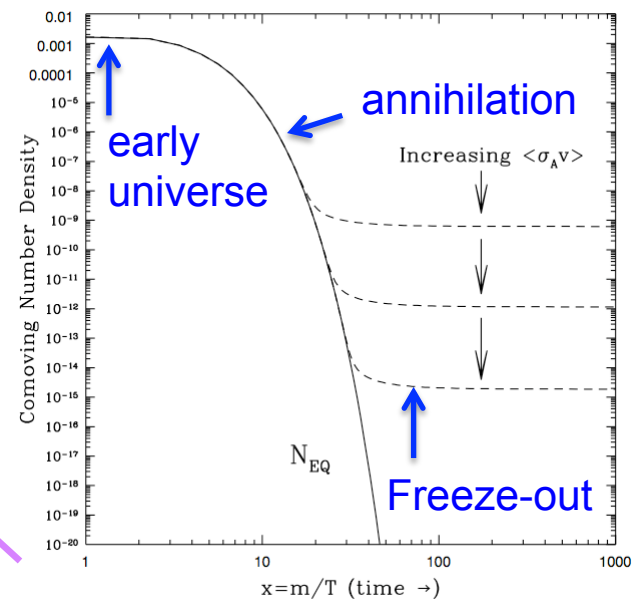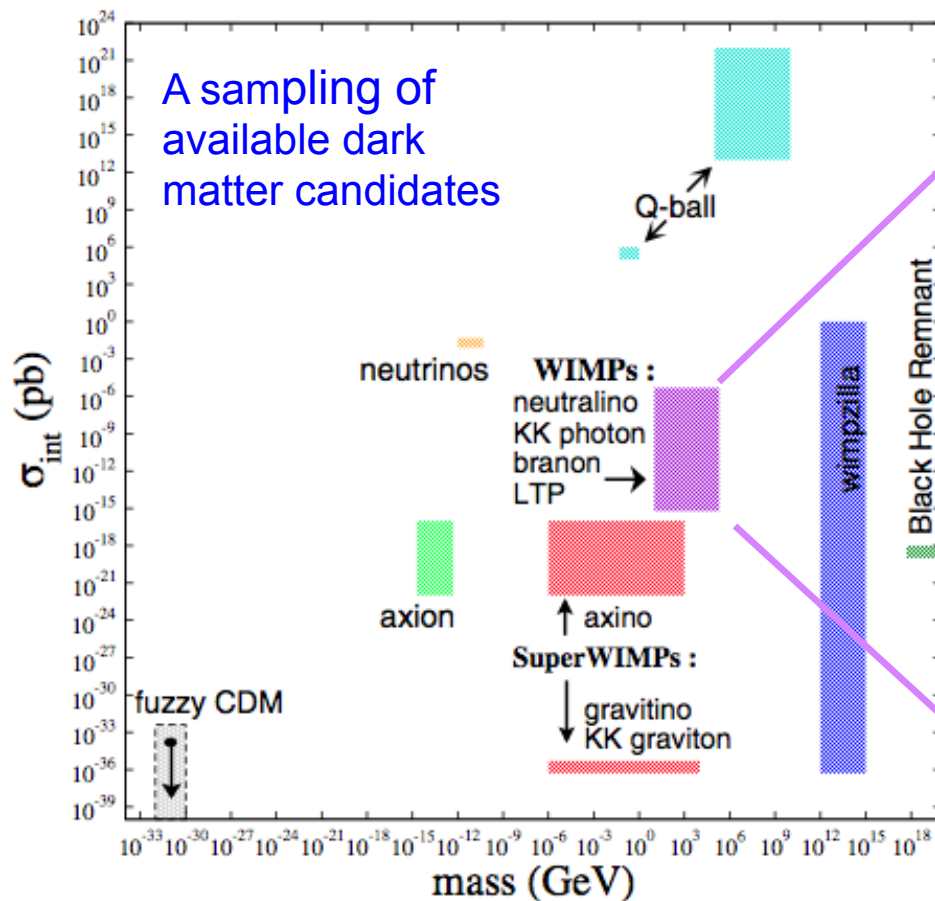If dark matter is composed of elementary particles, none in the Standard Model fits !

WIMPs 101
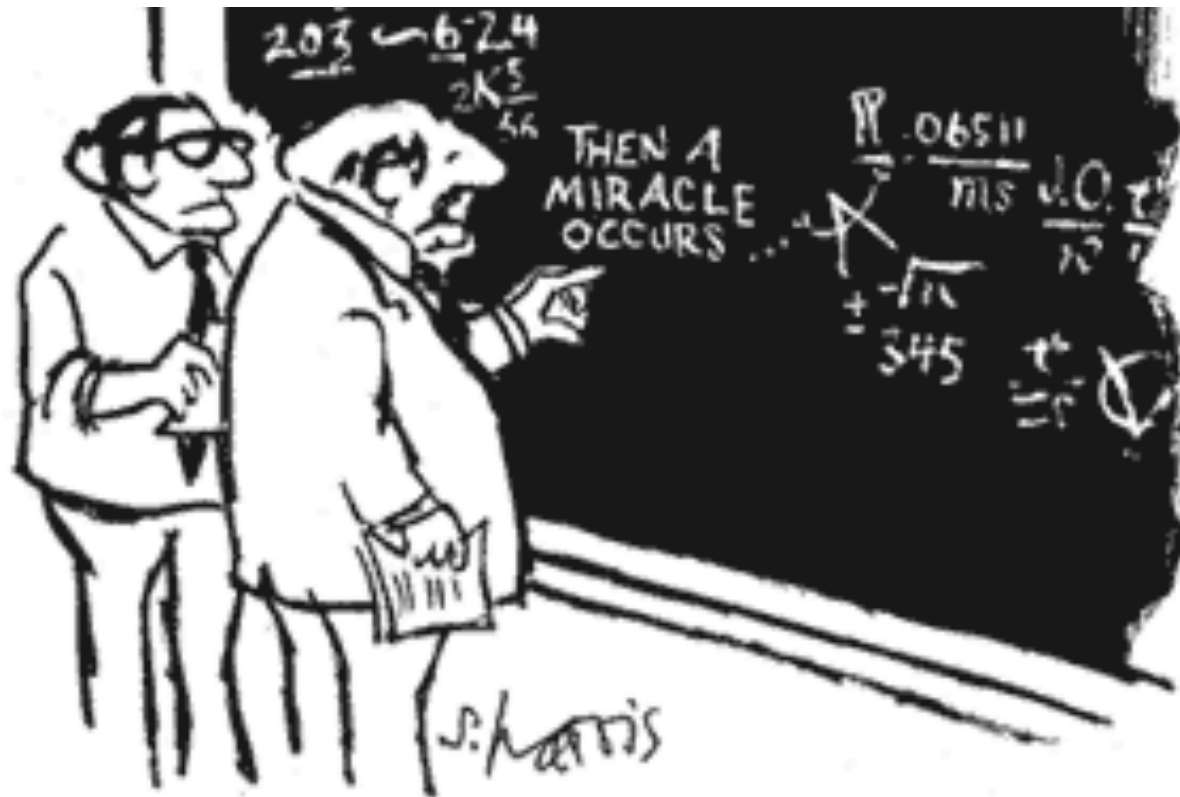
The Weakly Interacting Massive Particle

The WIMP "Miracle"
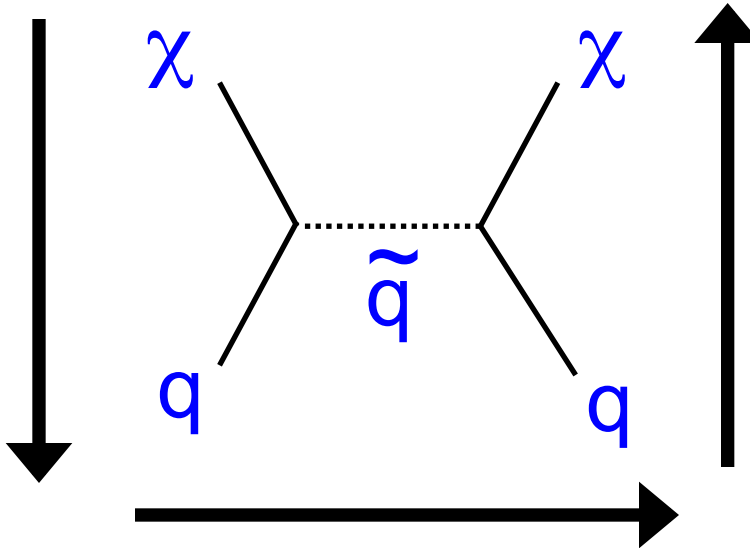
A sampling of available dark matter candidates

Particles with mass and couplings at the weak scale yield cross sections that correspond to ~correct relic density of CDM

How to detect WIMPs
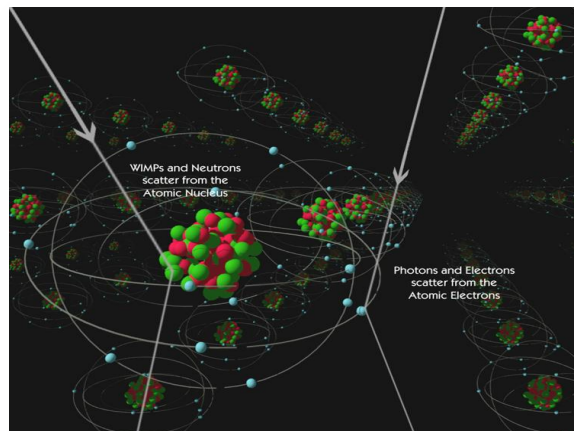

FERMI-GLAST
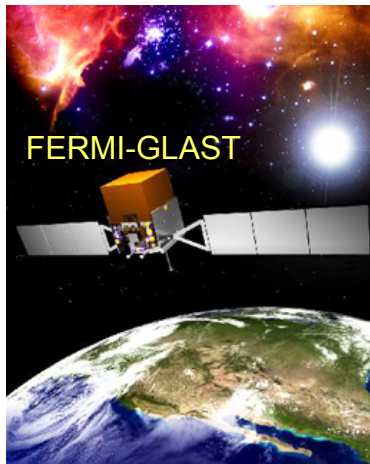
Relic annihilation in the cosmos

INDIRECT DETECTION

χ   χ

q̃

q   q

M. Attisha

WIMPs and Neutrons scatter from the Atomic Nucleus

Photons and Electrons scatter from the Atomic Electrons
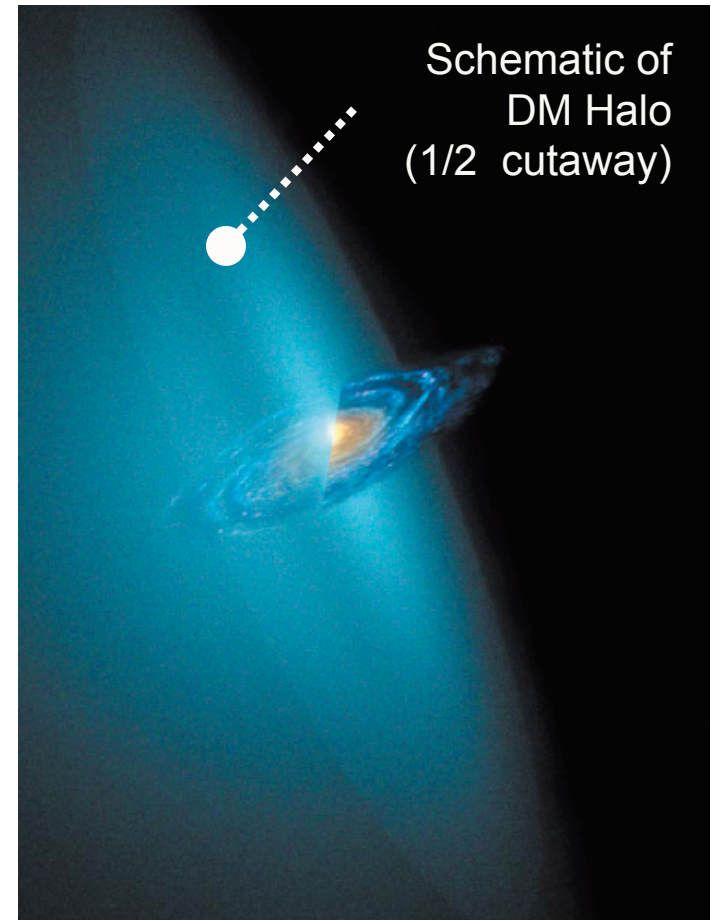
LHC

man-made COLLIDER production

Relic WIMP-nucleon elastic scattering

DIRECT DETECTION

Consider the relic WIMP distribution

Observed energy spectrum & rate depend on WIMP distribution in dark matter halo

- **Dark matter is distributed in a large extended, spherical halo around the Milky Way**

- **For comparison of direct detection experiments, assume an isothermal Maxwell-Boltzmann velocity distribution, with width = 220 km/s and v_{esc} = 544 km/s**

- **Ve ~ 245 km/s - WIMP velocity relative to Earth**

- **Local density of WIMPs = 0.3 GeV/cm^3**

If WIMPs are 100 GeV/c^2 particles, then ~10 million pass through your hand each second!

Schematic of DM Halo (1/2 cutaway)

Scattering rate dissected

Interaction Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \; \frac{F^2(E_R)}{m_r^2} \; \frac{\rho_o \, T(E_R)}{v_o \sqrt{\pi}}$$

particle theory

nuclear structure

local properties of DM halo

Recoil energy of nucleus

Scattering rate dissected

	particle theory	nuclear structure	local properties of DM halo

Interaction Rate [events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \; \frac{F^2(E_R)}{m_r^2} \; \frac{\rho_o \, T(E_R)}{v_o \, \sqrt{\pi}}$$

$$\sigma_o \simeq \frac{4m_r^2}{\pi} f A^2 \;\longleftarrow$$

For spin-independent scattering, and small momentum transfer, scattering terms add coherently, proportional to A^2 (A= atomic mass)

WIMP-nucleon coupling constant; assumed same for proton and neutron in vanilla scattering

Scattering rate dissected

Interaction Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \underbrace{\frac{\sigma_o}{m_\chi}}_{\text{particle theory}} \underbrace{\frac{F^2(E_R)}{m_r^2}}_{\text{nuclear structure}} \underbrace{\frac{\rho_o \, T(E_R)}{v_o \, \sqrt{\pi}}}_{\text{local properties of DM halo}}$$

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

Reduced mass of WIMP-nucleon system

Form factor parameterizes "coherence" vs E_r

$$F(E_R) \simeq \exp\left(-E_R \, m_N \, R_o^2/3\right)$$

Scattering rate dissected

	particle theory	nuclear structure	local properties of DM halo

Interaction Rate [events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \; \frac{F^2(E_R)}{m_r^2} \; \frac{\rho_o \, T(E_R)}{v_o \sqrt{\pi}}$$

Integral over local WIMP velocity distribution (Maxwell-boltzmann w/ assumed parameters on earlier slide)

$$T(E_R) \simeq \cdot \int_{v_{min}}^{\infty} \frac{f(\boldsymbol{v}_D, \boldsymbol{v}_E, v_{esc})}{v_D} \, \mathrm{d}v_D$$
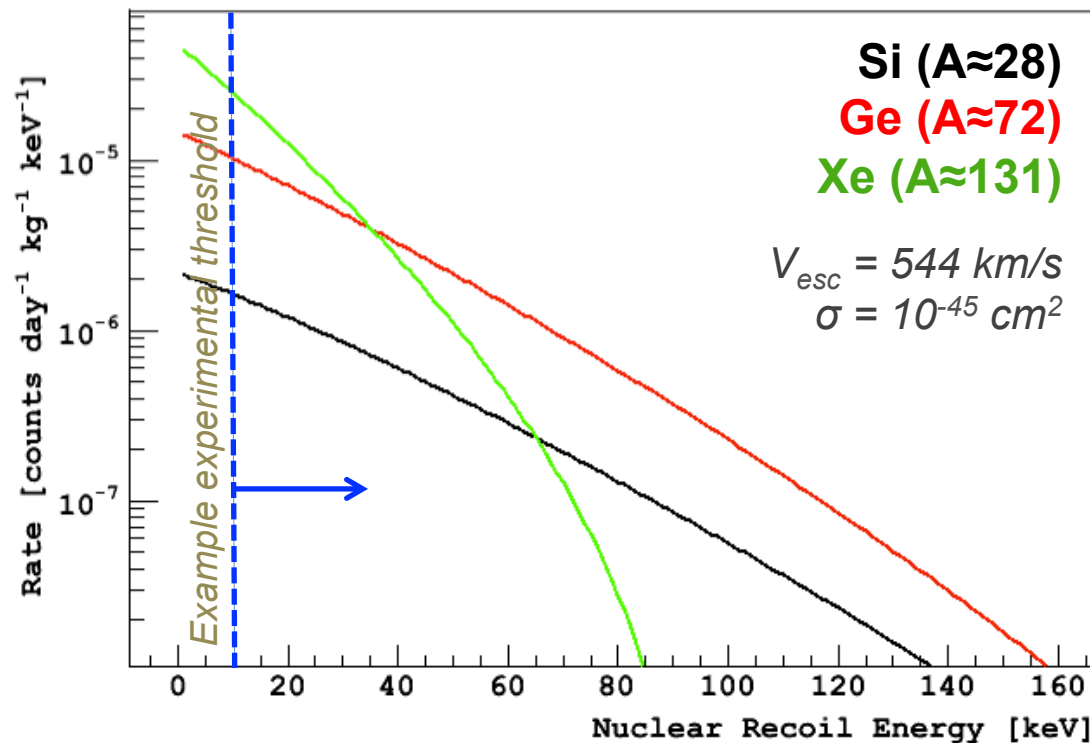
$$v_{\min} = \sqrt{E_R \, m_N / (2 m_r^2)}$$

V_{min} is the minimum WIMP velocity needed to produce recoil E_r

The expected signal from a heavy WIMP

Expected recoil spectrum is roughly exponential with << 1 event/kg/day expected, A^2 enhancement helps a lot with heavy WIMPs

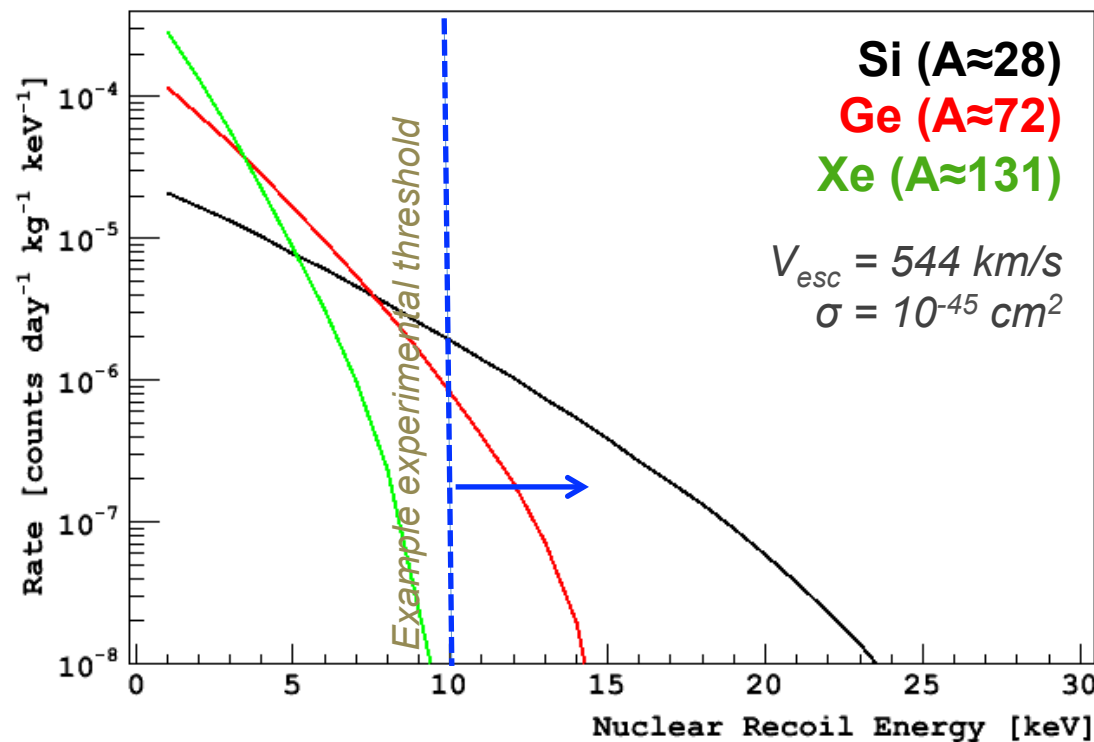100 GeV/c^2 WIMP-induced recoil spectrum

Si (A≈28)
Ge (A≈72)
Xe (A≈131)
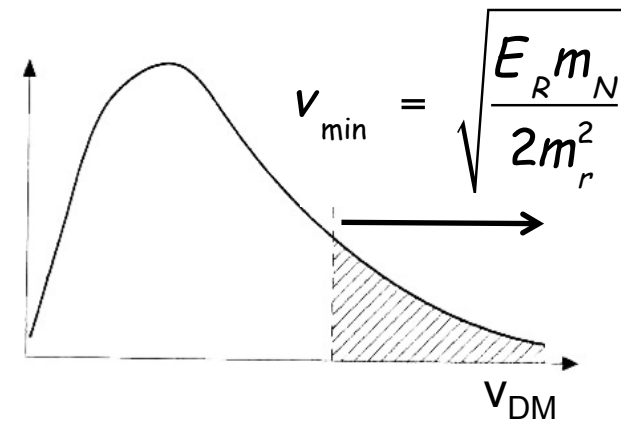
V_{esc} = 544 km/s
σ = 10^{-45} cm^2

The expected signal from a light WIMP

Recoil spectrum drops off much more steeply with energy because kinematics matter much more for light WIMPs !

10 GeV/c^2 WIMP-induced recoil spectrum

A WIMP must have a minimum velocity to produce a recoil of a specific energy

Si (A≈28)
Ge (A≈72)
Xe (A≈131)

V_{esc} = 544 km/s
σ = 10^{-45} cm^2

$$v_{min} = \sqrt{\frac{E_R m_N}{2m_r^2}}$$

→ *Experiments with lighter targets and lower thresholds have the advantage when looking for WIMPs with mass < 10 GeV/c^2*
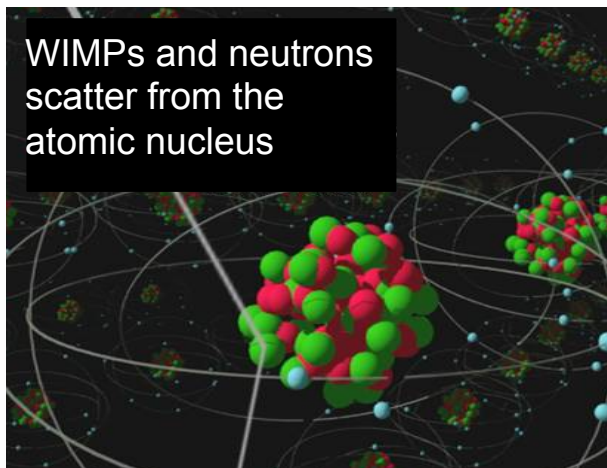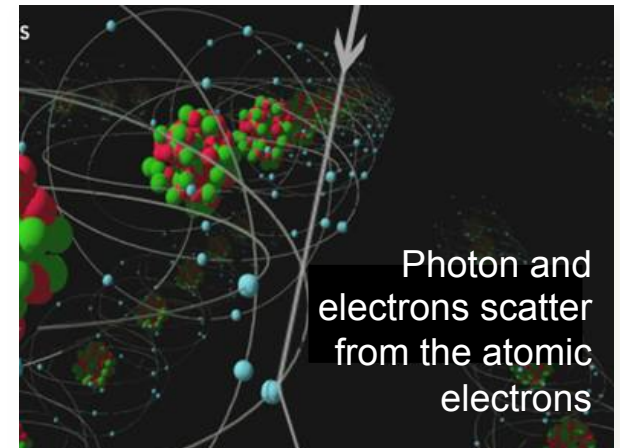
Backgrounds: as big a problem as ever

Expected WIMP scattering rate is ~10^7 times lower than radioactivity of common materials

ELECTRON RECOILS

Gamma: MOST PREVALENT BACKGROUND

Beta: most common "surface events"

Photon and electrons scatter from the atomic electrons

WIMPs and neutrons scatter from the atomic nucleus
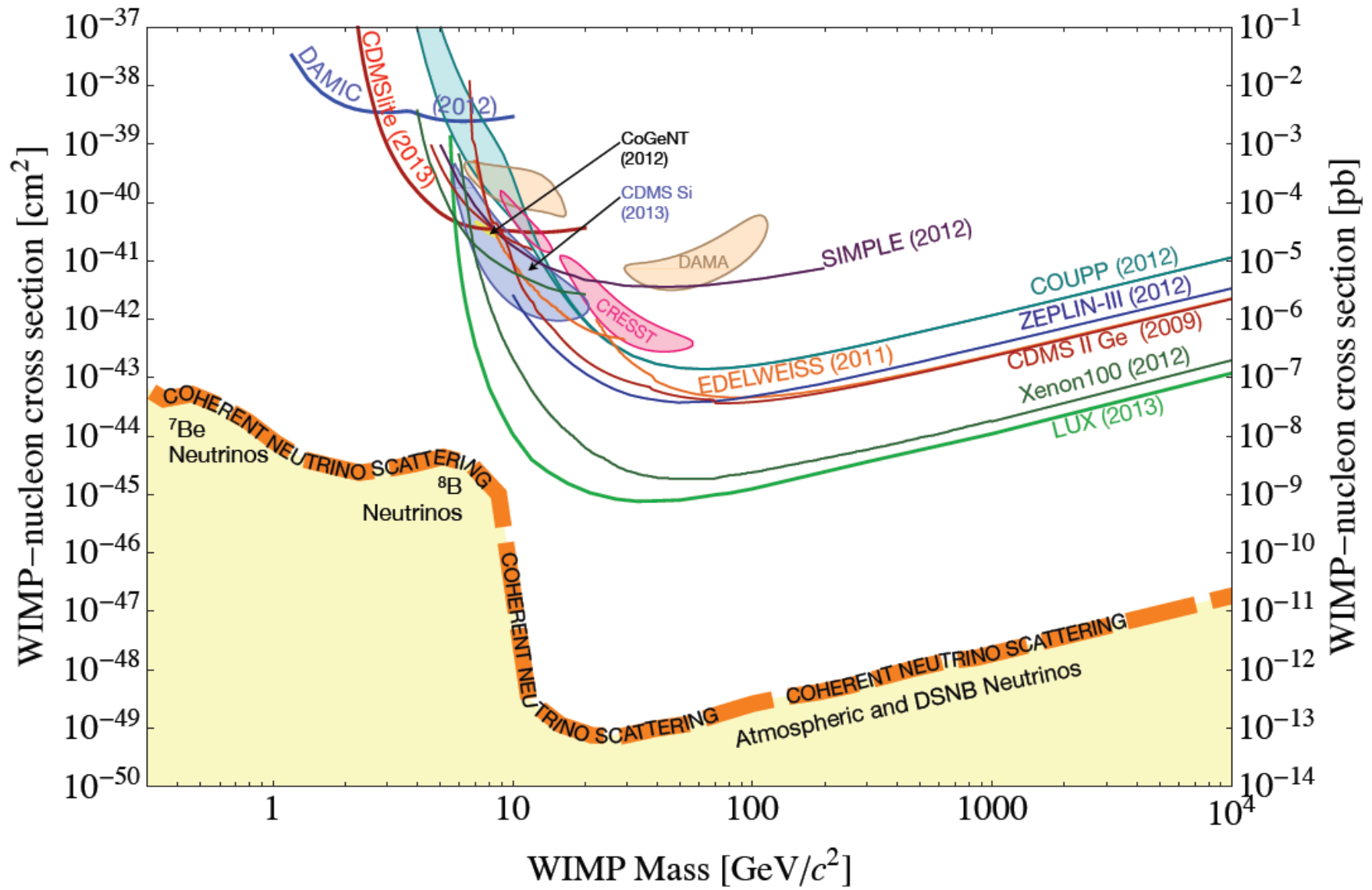
NUCLEAR RECOILS

Neutron: rare but single-scatters NOT distinguishable from a WIMP signal
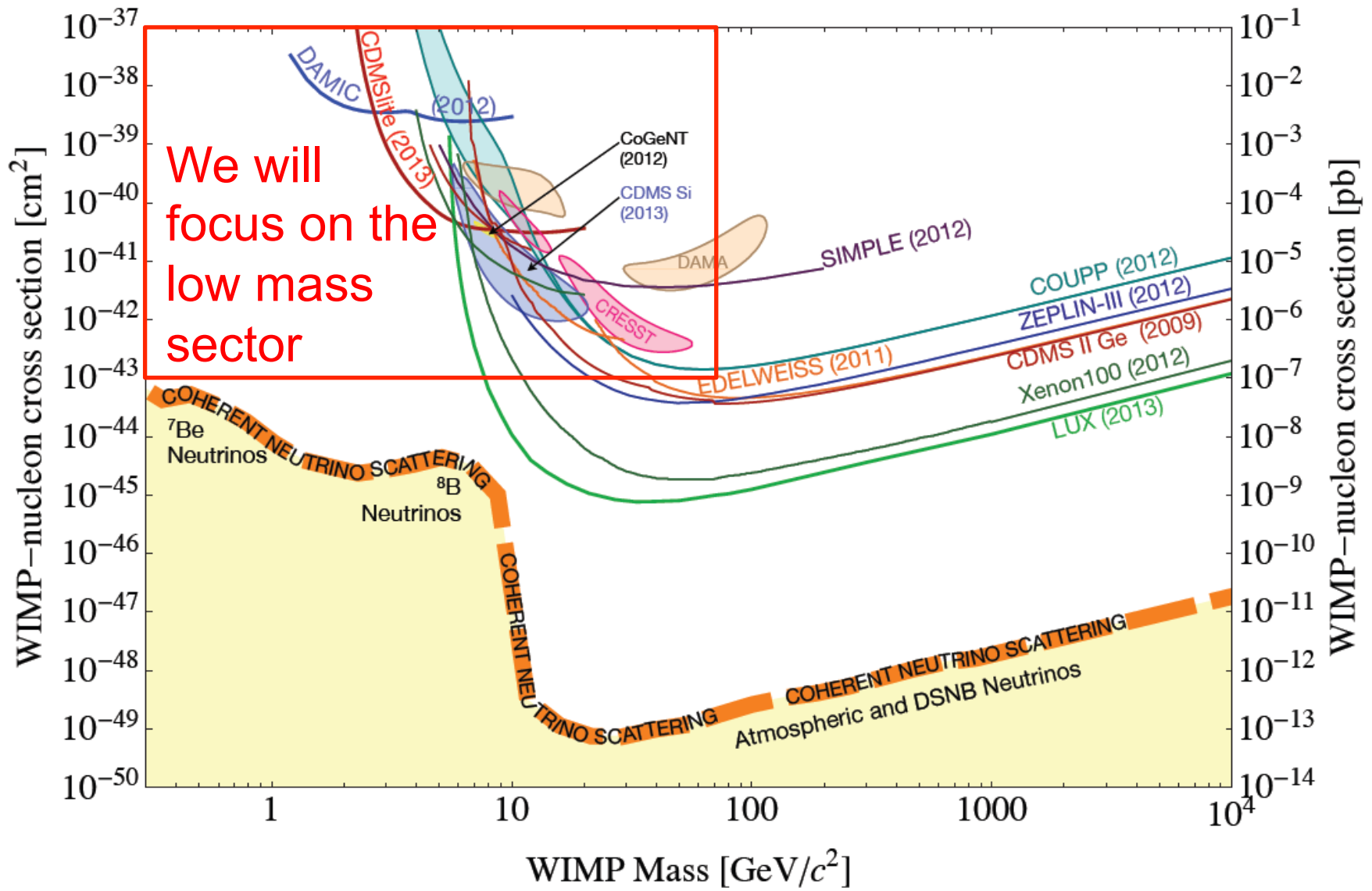
Alphas: not a background for CDMS

Pb recoils (from alpha decay): another type of surface event background
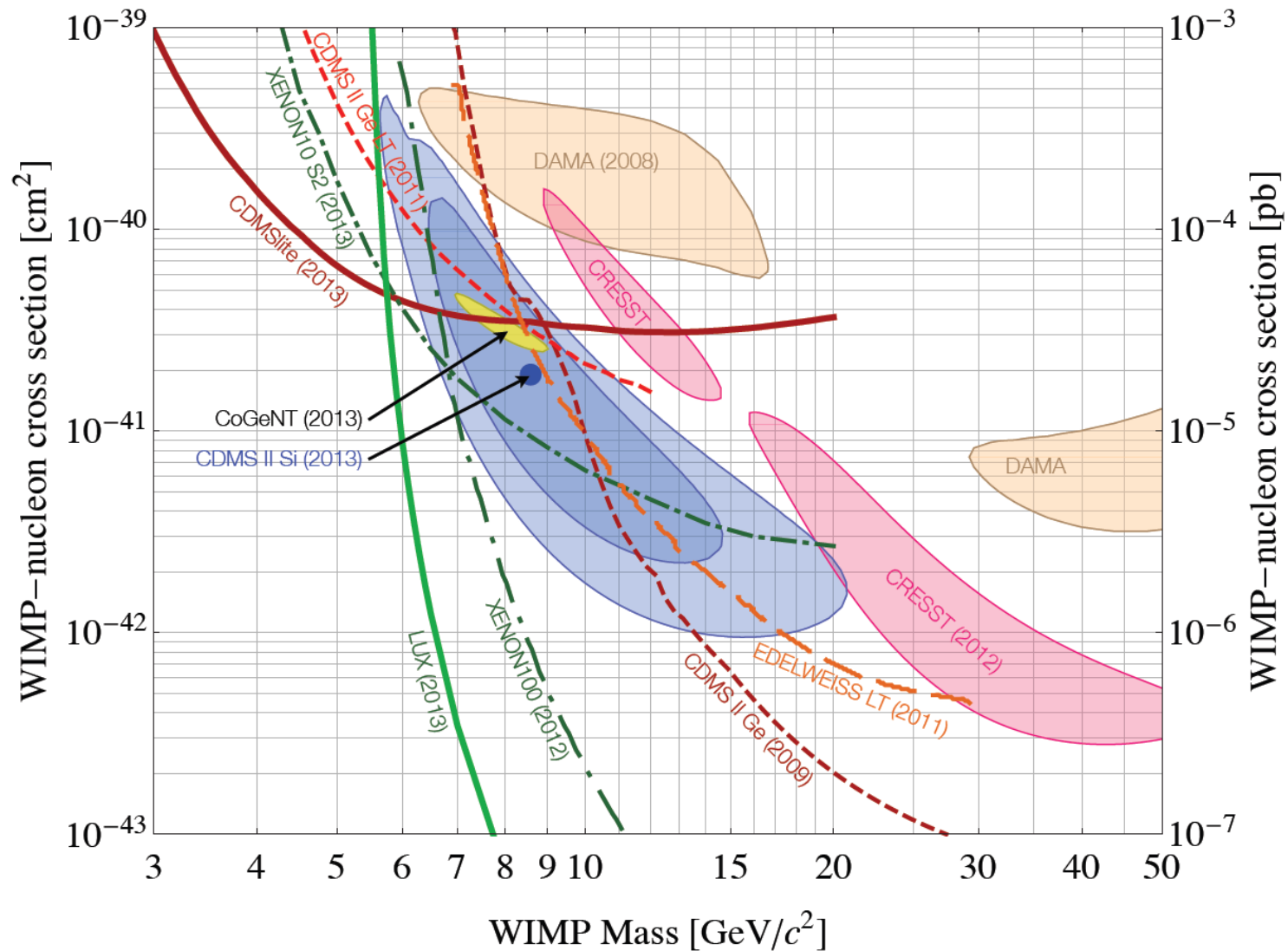
Have we seen evidence for WIMPs?
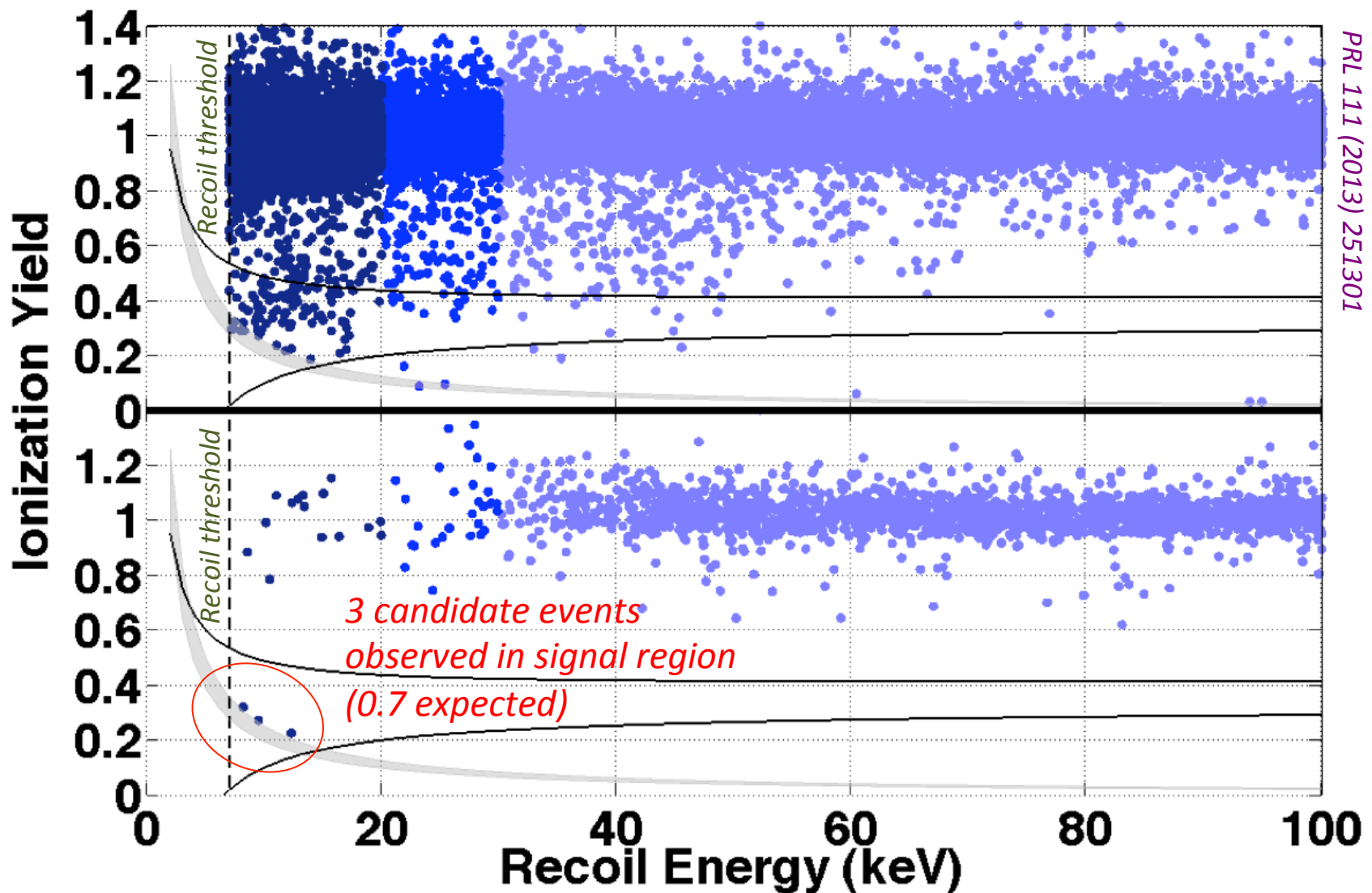
Spin-Independent Landscape

Spin-Independent Landscape
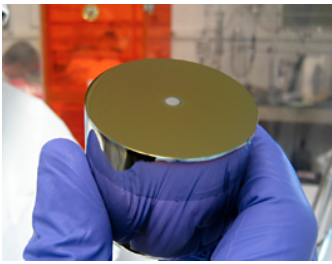
Zoom of Low-Mass Region

Hint from CDMS II Silicon Search

Ionization Yield (y-axis)

Recoil threshold

3 candidate events observed in signal region (0.7 expected)

Recoil Energy (keV) (x-axis)

*Likelihood analysis incorporating energy of events yields ~3σ significance*

Recent updates to earlier hint: CoGeNT

In 2010, CoGeNT using PPC Ge to push ionization thresholds down to <0.5 keV; reported an excess of low-energy events with spectrum consistent with a ~10 GeV/c^2 WIMP

In 2011, reports a modulation of events in the 0.5-3.0 keVee region with ~2σ significance, corresponding to a large fractional modulation

In 2014, Analysis of 3.4 years of data shows persistent ~2σ modulation in low-energy region, *arXiv:1401.3295*; Alternative maximum likelihood analysis qualitatively supports earlier analysis, but with less significant excess seen at low energies, *arXiv:1401:6234*.
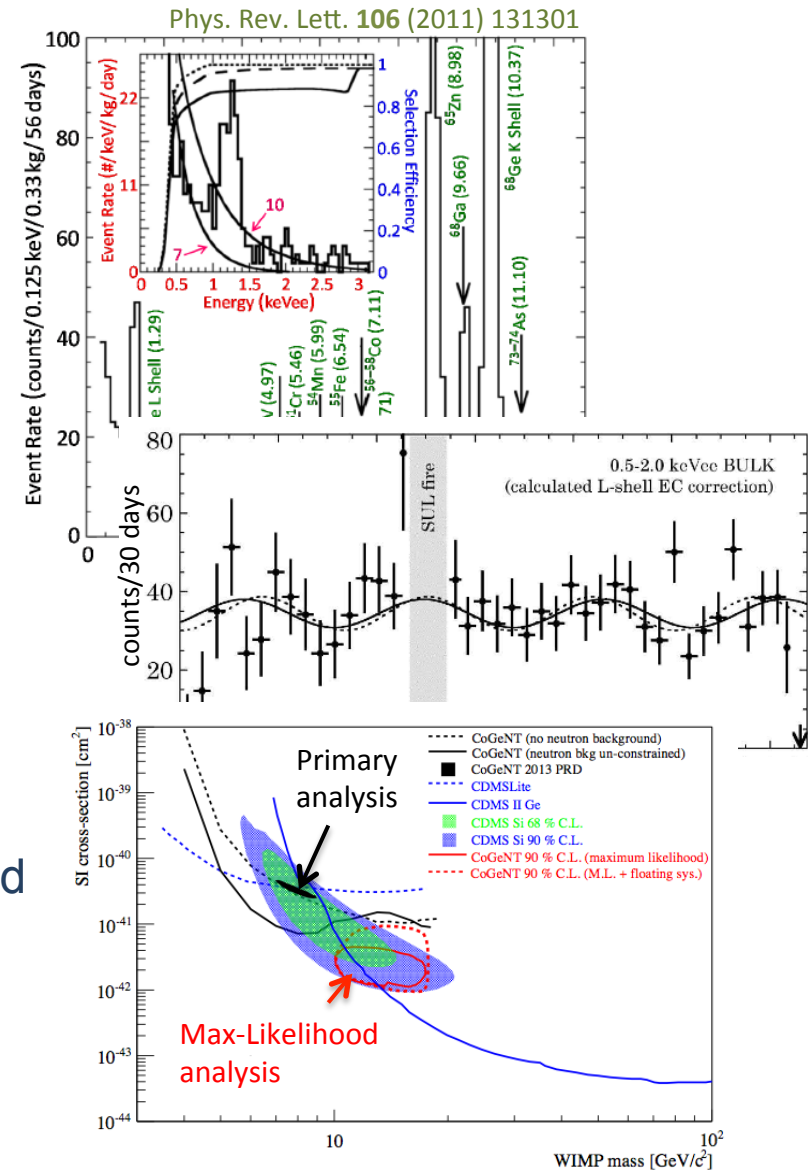
Phys. Rev. Lett. **106** (2011) 131301

Primary analysis

Max-Likelihood analysis

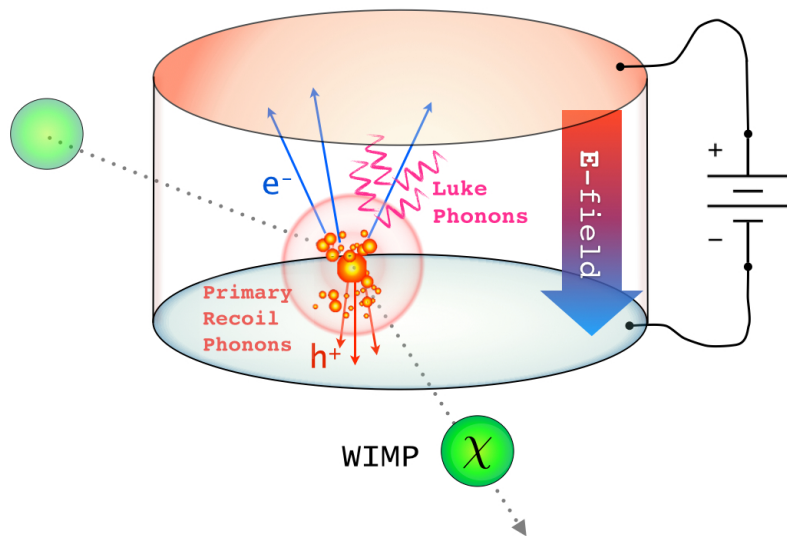# (Ultra) Low Ionization Threshold Experiment: CDMSlite

Neganov-Luke amplification of phonon response allows operation at very low energy thresholds
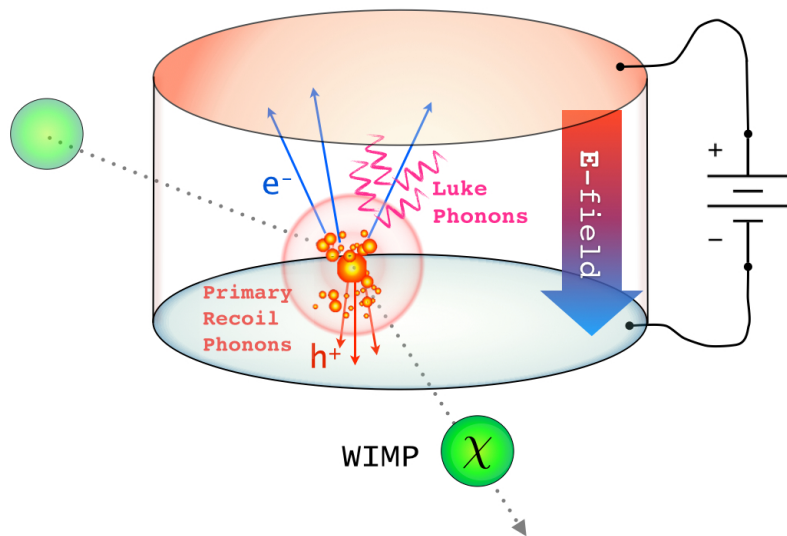
Electrons and holes radiate phonons proportional to V_{bias} as they drift to the electrodes. ➔ Apply large V_{bias} to amplify ionization signal

(Ultra) Low Ionization Threshold Experiment: CDMSlite

Neganov-Luke amplification of phonon response allows operation at very low energy thresholds

e⁻ → e^- Luke Phonons

E-field

Primary Recoil Phonons h^+

WIMP χ

CDMSlite (2014)

σ_{SI} [cm^2]

World-leading limit w/ ~10 day exposure!

10^{-40}

10^{-41}

3 4 5 6 8 10 12 18
m_χ [GeV/c^2]

Electrons and holes radiate phonons proportional to V_{bias} as they drift to the electrodes. ➔ Apply large V_{bias} to amplify ionization signal
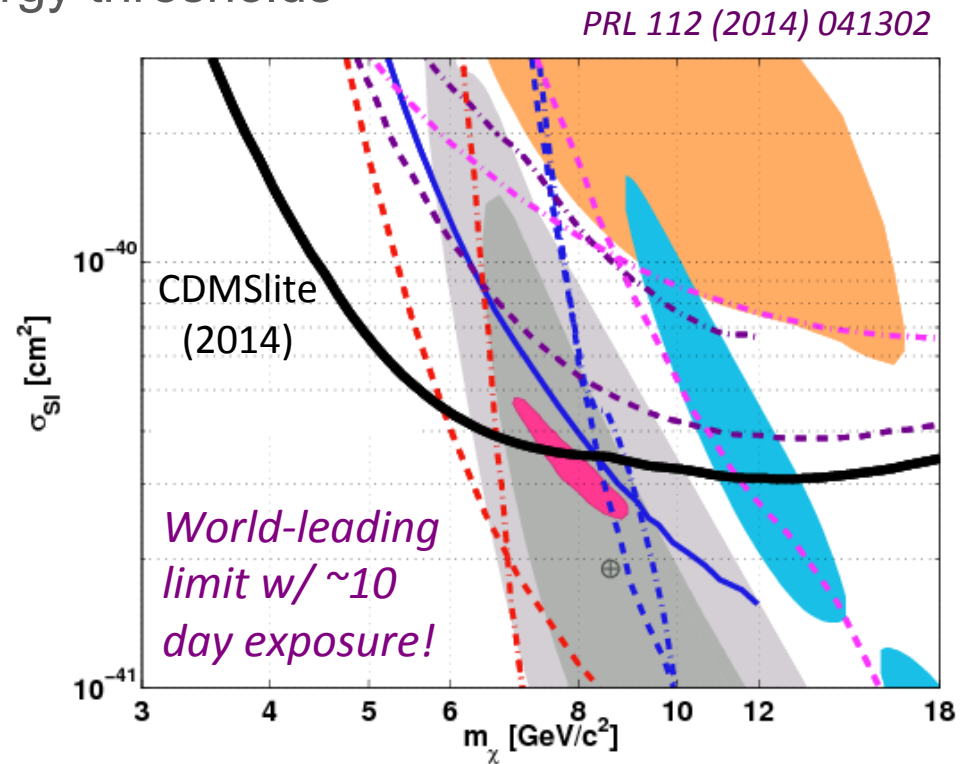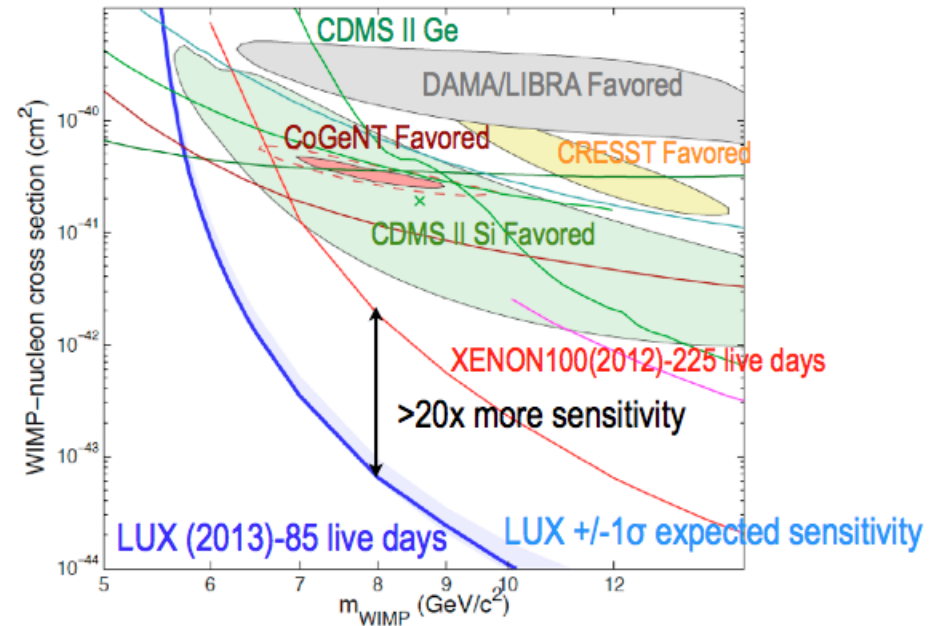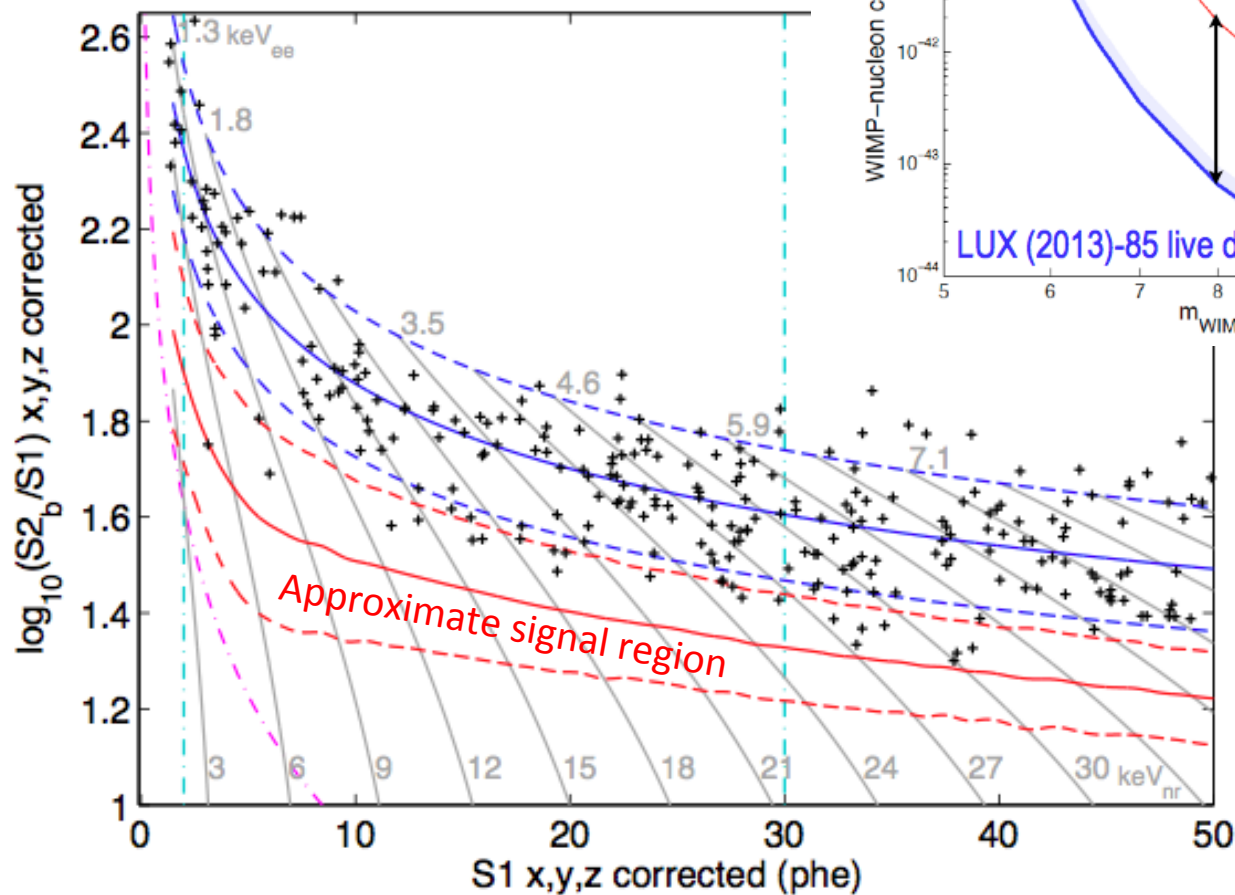
First CDMSlite run: 170 eVee (<1 keV$_{nr}$) threshold with 0.6 kg Ge, 10 live days and no background subtraction!

First Results from LUX

85.3 live days with
118 kg Xe target, operated in
dual-phase TPC; Sets world's most
sensitive SI limit over broad mass range

Large enough mass can give sensitivity to some low mass WIMPs. But be careful with energy scale calibration and velocity profiles!

Why low mass?

Masses < 10 GeV/c^2 are not naturally preferred by many theoretical frameworks motivated by the WIMP miracle. However ….

- Many models predict dark matter outside of the "vanilla" WIMP paradigm. Fine tuning of parameters is often necessary, even if it's undesirable

- Expanding beyond CMSSM (even SUSY) opens up a lot of parameter space: *pMSSM, NMSSM, Asymmetric, Isospin Violating, Inelastic, (insert your favorite model here), …*

- We should not ignore the data. Several experiments are reporting excess events. Could these be the first indications of a major discovery? Several other experiments, done with different targets, are in tension with a dark matter interpretation…

Even if the experiments are only seeing backgrounds, its worth gathering enough data to definitively rule out these anomalous observations!
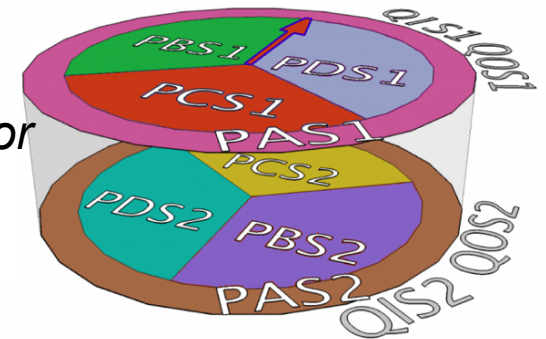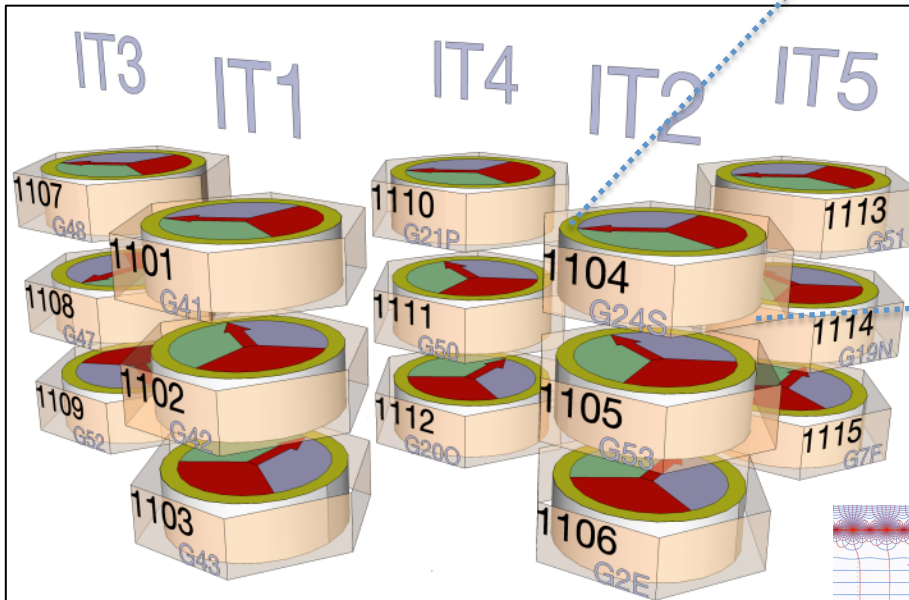
SuperCDMS Low-Mass WIMP Search
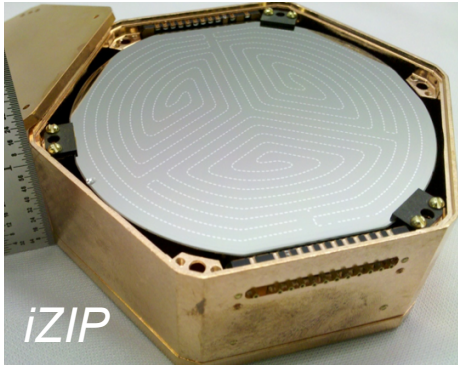
SuperCDMS Soudan

*iZIP*

interleaved
Z-sensitive
Ionization &
Phonon detector

Improved fiducialization from measurement
of z-symmetric ionization response
Phonon guard and z-symmetric phonon
response helps too!

IT3 IT1 IT4 IT2 IT5

1107 G48
1101 G41
1108 G47
1102 G42
1109 G52
1103 G43

1110 G21P
1111 G50
1112 G20O

1104 G24S
1105 G53
1106 G2E

1113 G51
1114 G19N
1115 G7E

15 germanium detectors
0.6 kg each
Operational since March of 2012

APL 103, 164105(2013)

h+   e-
-2V   0V

Data for this analysis: *577 kg-days*
taken from Mar 2012 – July 2013
7 iZIPs w/ lowest trigger thresh
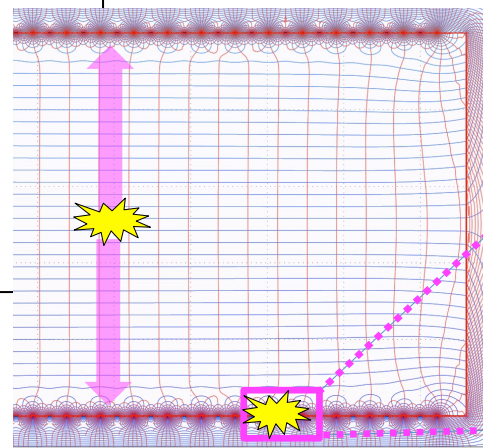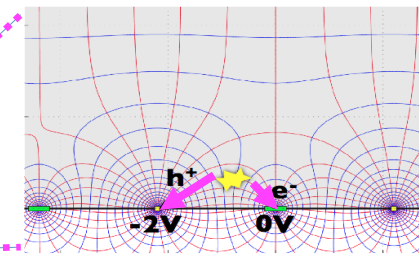
The SuperCDMS Collaboration

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U. Gennser, L. Couraud, Y. Jin

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T. Saab, B. Welliver

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D. Barker, H. Chagani, P. Cushman,
S. Fallows, T. Hofer, A. Kennedy,
K. Koch, V. Mandic, M. Pepin,
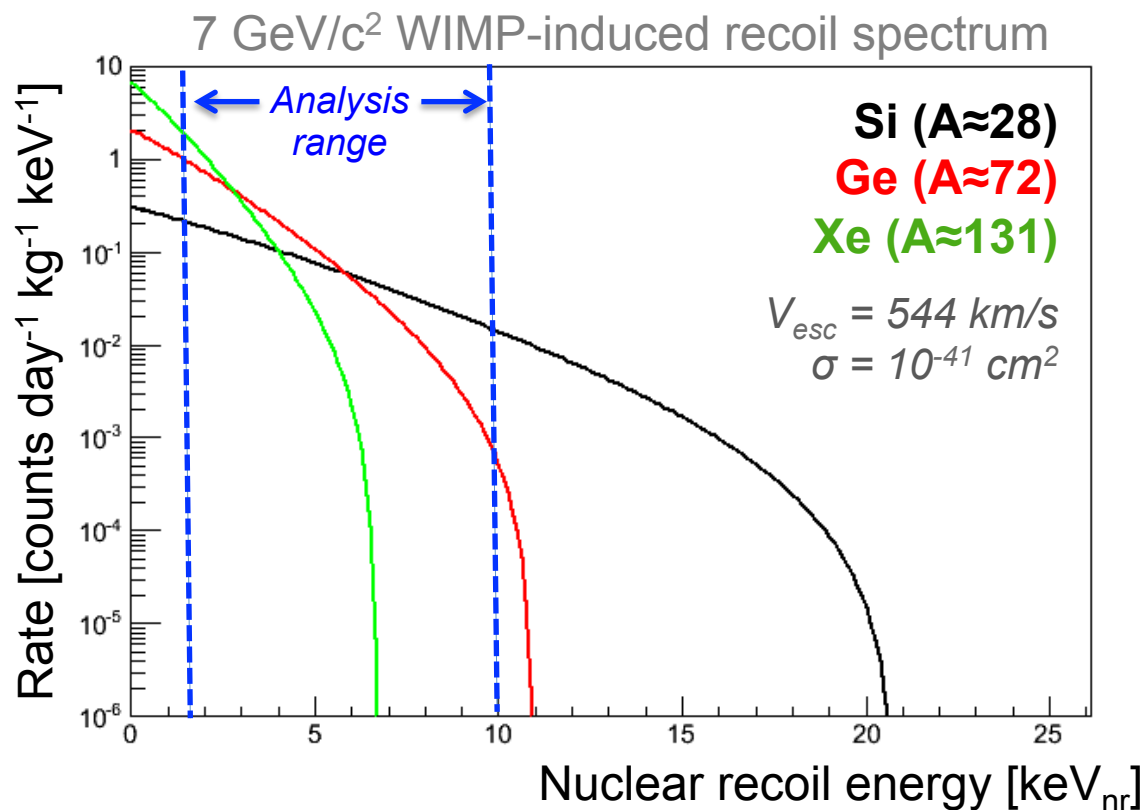H. Rogers, A.N. Villano, J. Zhang

U. South Dakota
J. Sander

Optimizing for Low Mass

Recall: experiments with lighter targets and lower thresholds have the advantage when looking for WIMPs with mass < 10 GeV/c²

7 GeV/c² WIMP-induced recoil spectrum

Our strategy:

Ge is a relatively heavy target so go as low in threshold as possible
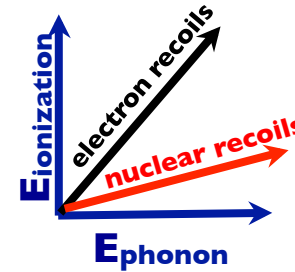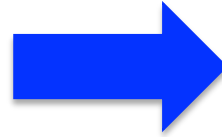➔ trigger threshold (1.6 keV$_{nr}$)

Backgrounds more difficult to reject below 10 keV$_{nr}$; use full capability of iZIPs to reject as much background as possible

We expect background events in the signal region!!   Tradeoff is greater sensitivity to low mass WIMPs.
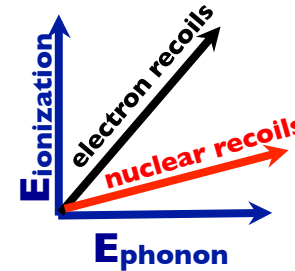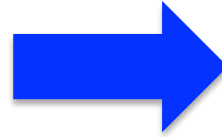
Backgrounds to Eliminate

Bulk electron recoils = Compton background and 1.3 keV activation line

Ionization vs phonon distinguishes NR from bulk ER

$E_{ionization}$

E_{phonon}
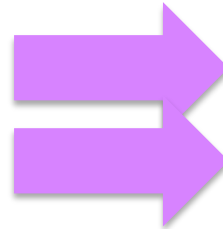
electron recoils

nuclear recoils

Backgrounds to Eliminate

Bulk electron recoils = Compton background and 1.3 keV activation line

Ionization vs phonon distinguishes NR from bulk ER

sidewall & surface events = betas and x-rays from ^{210}Pb, ^{210}Bi, recoils from ^{206}Pb (i.e. Rn daughters), outer radial comptons and ejected electrons from compton scattering
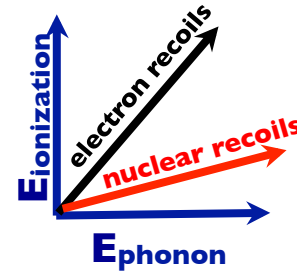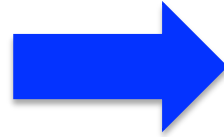
Use division of energy between inner and outer sensors, "radial partition"

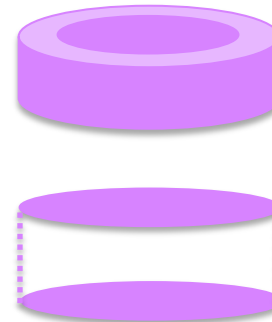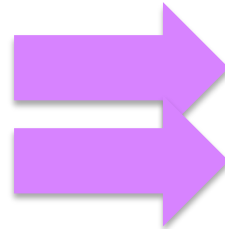*Use division of energy between sides 1 and 2, "z-partition"*

Backgrounds to Eliminate

Bulk electron recoils = Compton background and 1.3 keV activation line

Ionization vs phonon distinguishes NR from bulk ER

sidewall & surface events = betas and x-rays from ^{210}Pb, ^{210}Bi, recoils from ^{206}Pb (i.e. Rn daughters), outer radial comptons and ejected electrons from compton scattering

Use division of energy between inner and outer sensors, "radial partition"

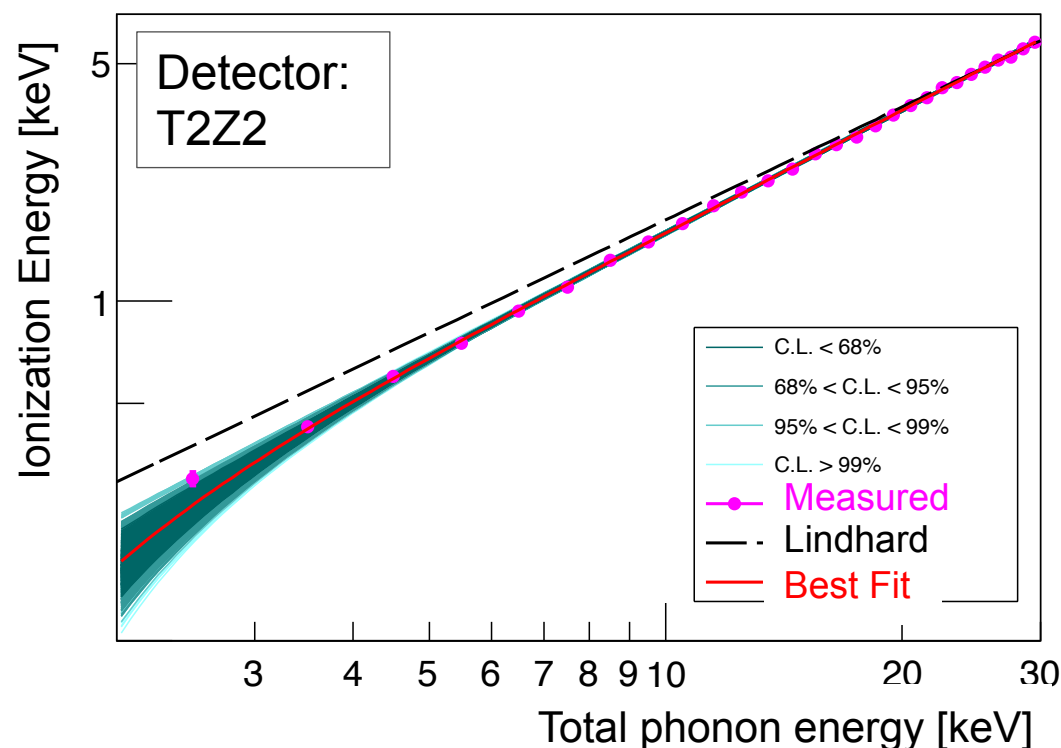*Use division of energy between sides 1 and 2, "z-partition"*

Cosmogenic & radiogenic neutrons

SuperCDMS Muon veto

Use active and passive shielding. Simulation determines remaining irreducible rate

Nuclear Recoil Energy Determination

*Ionization for nuclear recoils,
measured from ^{252}Cf data:*

Detector: T2Z2

Ionization Energy [keV]

5

1

C.L. < 68%
68% < C.L. < 95%
95% < C.L. < 99%
C.L. > 99%
Measured
Lindhard
Best Fit

3   4   5   6   7   8   9 10   20   30

Total phonon energy [keV]

Total phonon energy =
$$E_{total} = E_{luke} + E_{recoil}$$
E_{total} is measured with phonons

NR equivalent energy =
$$E_{total} - E_{Luke\ NR}$$
*$E_{Luke\ NR}$ estimated from mean NR
ionization, varies with E_{total}
(same as CDMS II low mass
search)*

*Note: we sometimes approximate mean ionization with Lindhard theory because
measured values are detector-dependent.   This is labeled "Lindhard nuclear recoil
energy"; difference is a few %.*

Analysis Summary

<u>Blind analysis:</u> All singles in analysis energy range removed from study, except data following neutron calibration due to activation (additional 97 kg-days not used for limit calculation or cut tuning)

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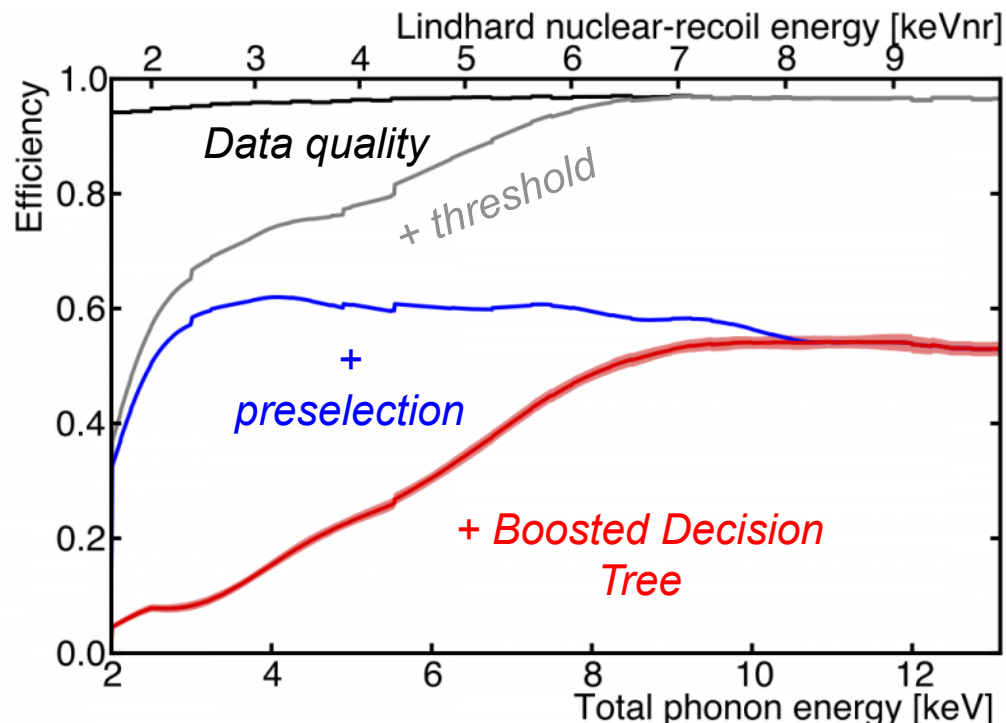
Efficiencies: *measured with neutrons from* ^{252}*Cf. Geant4 used to correct for multiple scattering, yields ~25% correction*

Data Quality:
- Reject high/abnormal noise
- Reject atypical operational periods

Trigger and Analysis Threshold:
- Select periods of stable, well-defined trigger threshold
- Analysis thresholds based on time-varying noise baseline
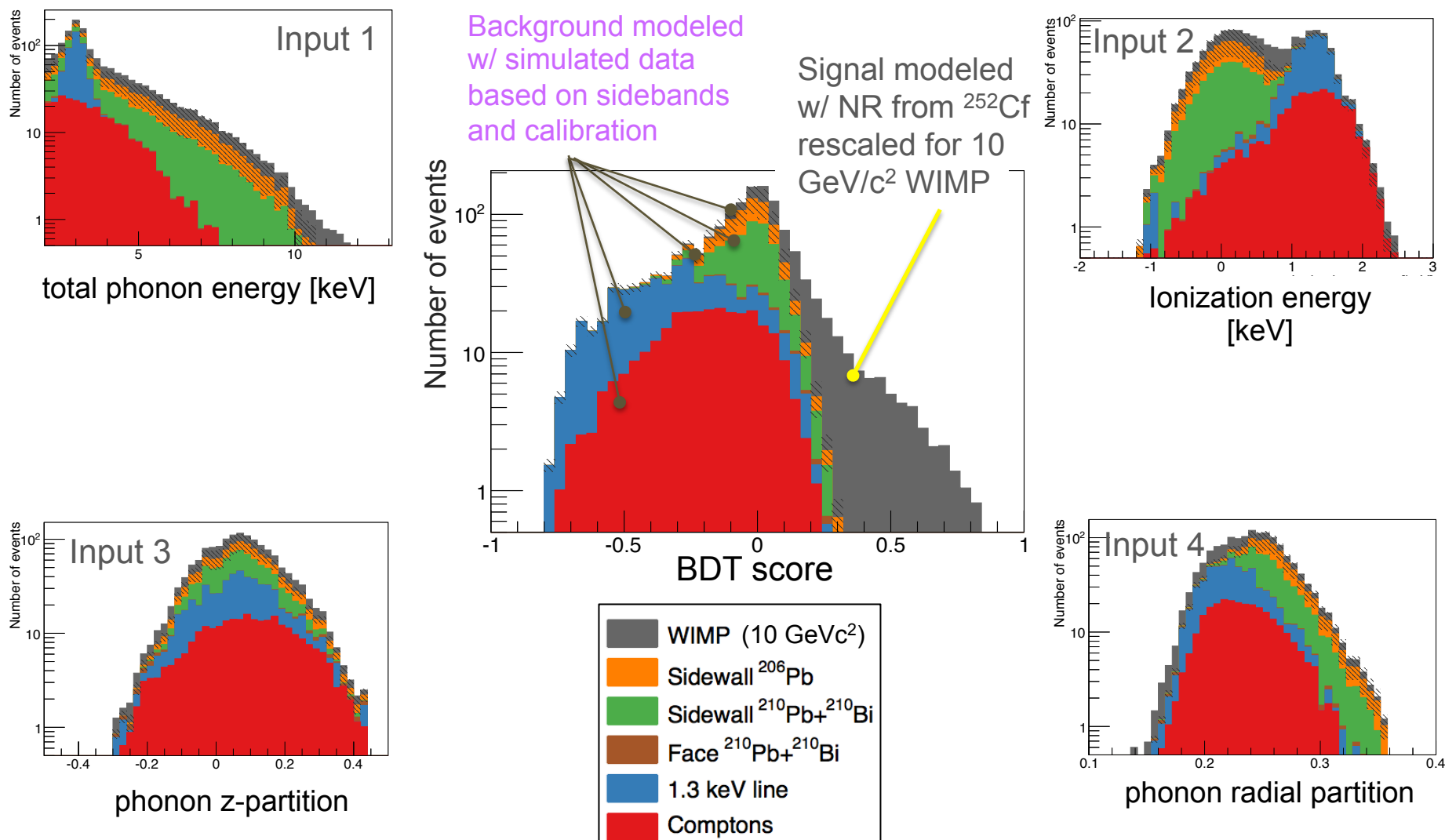
Preselection:
- Single-detector scatter
- Muon veto anticoincident
- ionization fiducial volume
- Ionization energy and phonon partitions consistent w/ NR

Boosted Decision Tree
- "tight" phonon fiducial volume and ionization yield at low energy
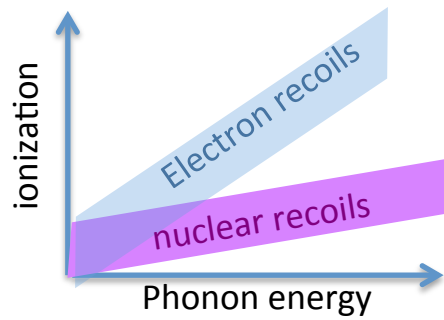
Boosted Decision Tree (BDT)

Discrimination lies in correlations between 4 parameters in partition and energy

Input 1 — total phonon energy [keV]

Background modeled w/ simulated data based on sidebands and calibration

Signal modeled w/ NR from ^{252}Cf rescaled for 10 GeV/c^2 WIMP

Input 2 — Ionization energy [keV]

BDT score — Number of events

Input 3 — phonon z-partition

Input 4 — phonon radial partition

Legend:
- WIMP (10 GeVc^2)
- Sidewall ^{206}Pb
- Sidewall ^{210}Pb+^{210}Bi
- Face ^{210}Pb+^{210}Bi
- 1.3 keV line
- Comptons

WIMP model assumes:
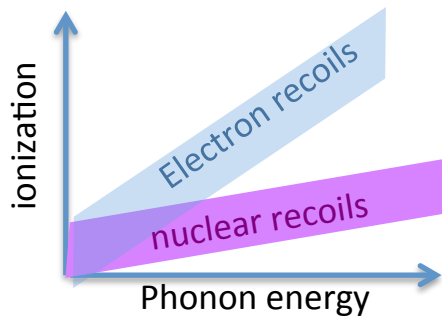$\sigma = 6 \times 10^{-42}$ cm^2

Background model w/ pulse simulation

Problem: *Backgrounds at low energy are more difficult to separate from signal region due to worsening resolution*

Background model w/ pulse simulation

ionization

Electron recoils

nuclear recoils

Phonon energy

Problem: Backgrounds at low energy are more difficult to separate from signal region due to worsening resolution

Solution: Study directly with a pulse simulation; using high energy events in sidebands and calibration data as templates

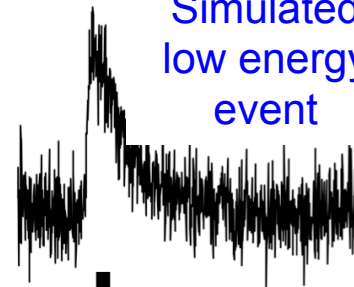Event w/ good signal to noise, scaled down in amplitude
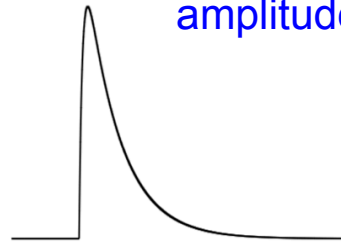
Random trigger (e.g. noise)

+

Simulated low energy event

=

reconstruction software

weight events as a function of energy to match low energy backgrounds

Background estimates

Background estimates finalized <u>before</u> unblinding, included known systematic effects;   Checked against open dataset and reasonable agreement found

*Purpose of background model was tuning cuts; possible unknown systematics preclude background subtraction for this blind analysis. *Thus, decision made to set an upper limit prior to unblinding*

4 BDT cuts developed for 5, 7, 10 and 15 GeV/c^2 WIMPs; accept events that pass any of the four cuts; Each cut was tuned simultaneously on all detectors, maximizing 90% C.L. poisson sensitivity for that mass

Background model expected: **6.1** $^{+1.1}_{-0.8}$ events

Neutron background adds additional: **0.10 ± 0.02** events
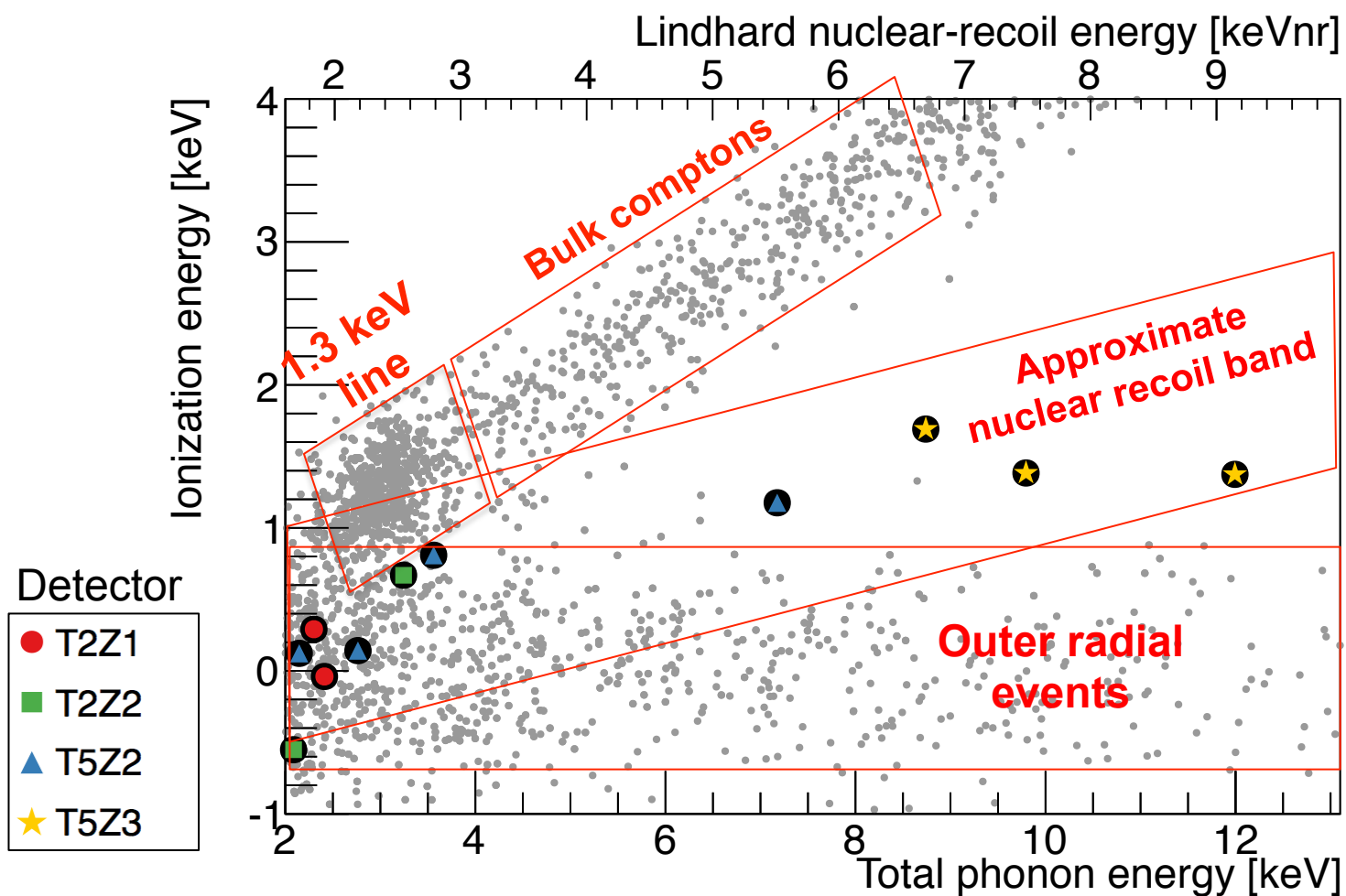
Unblinding: *Before BDT cut*

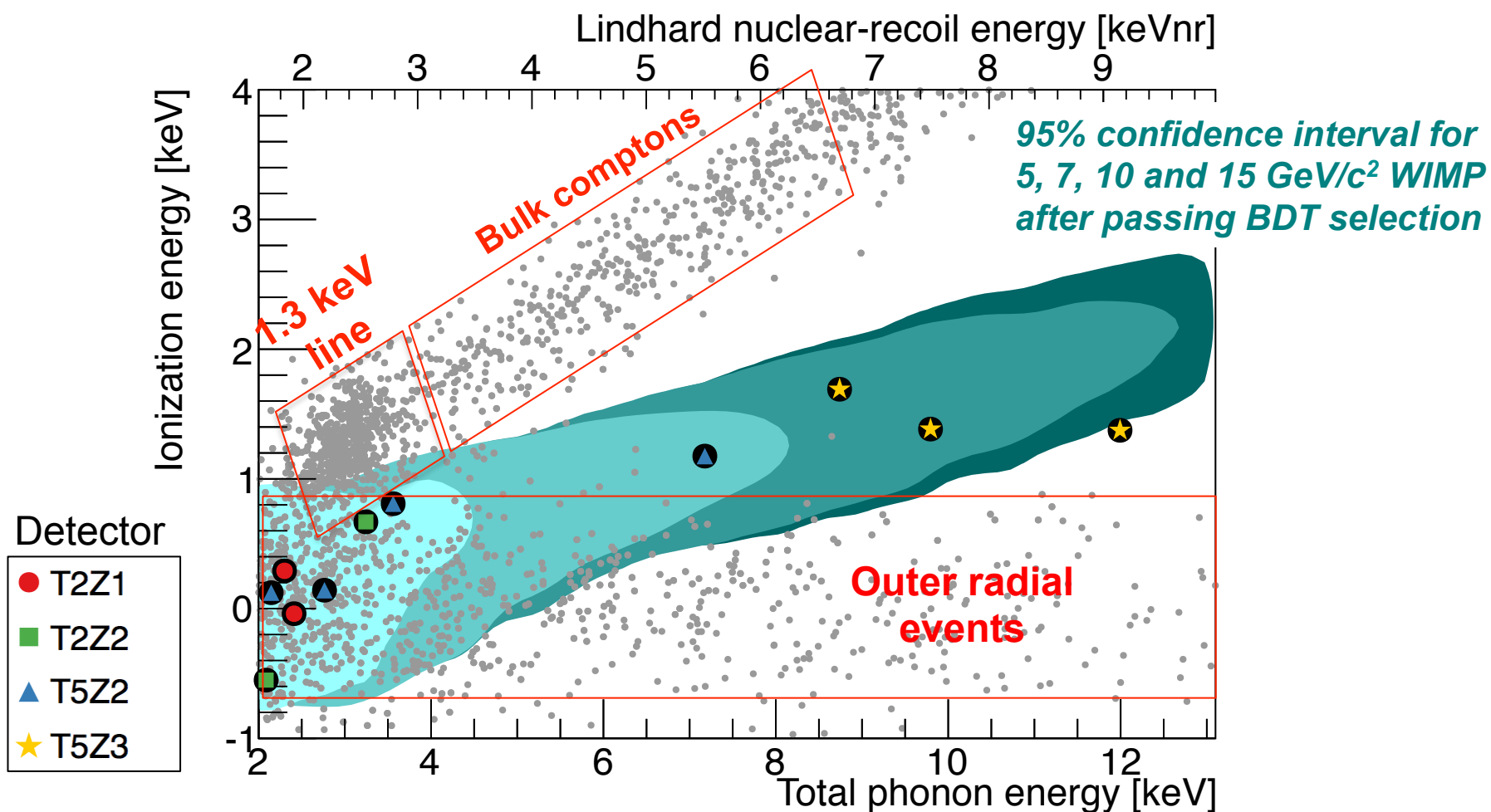*Shown: events passing all cuts except the BDT and ionization selection*
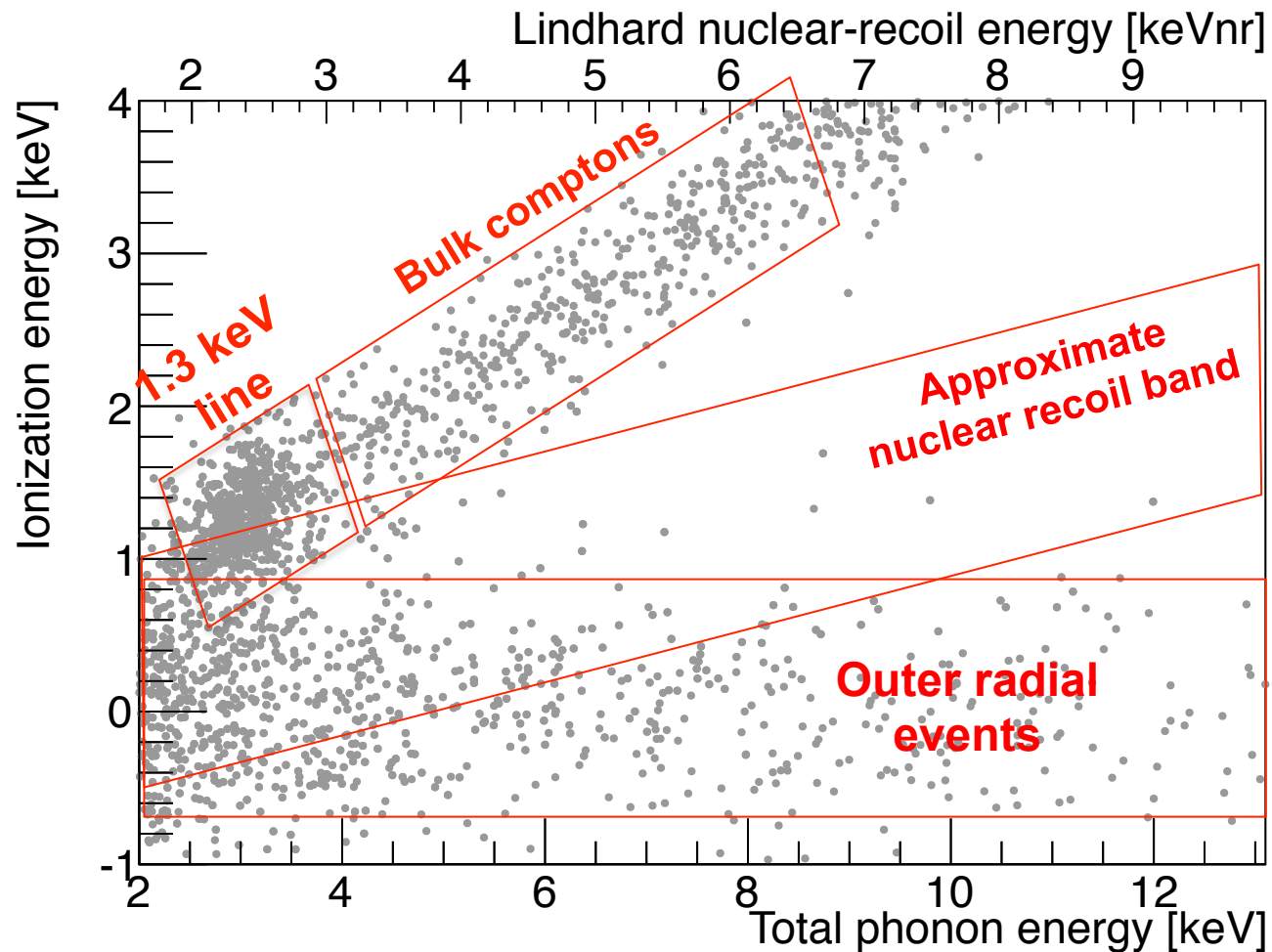
Unblinding: *After BDT cut*
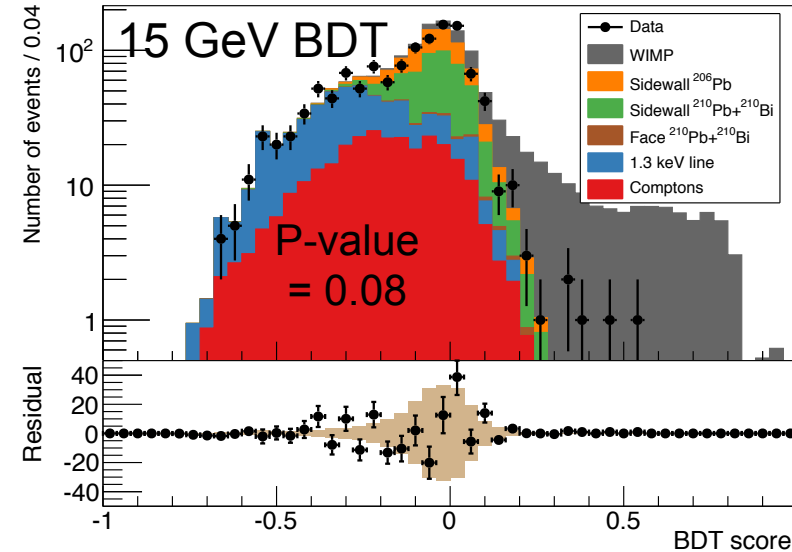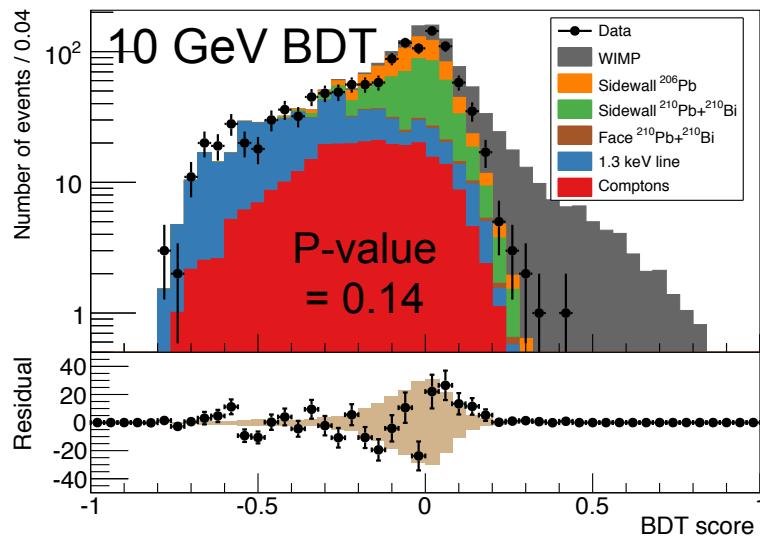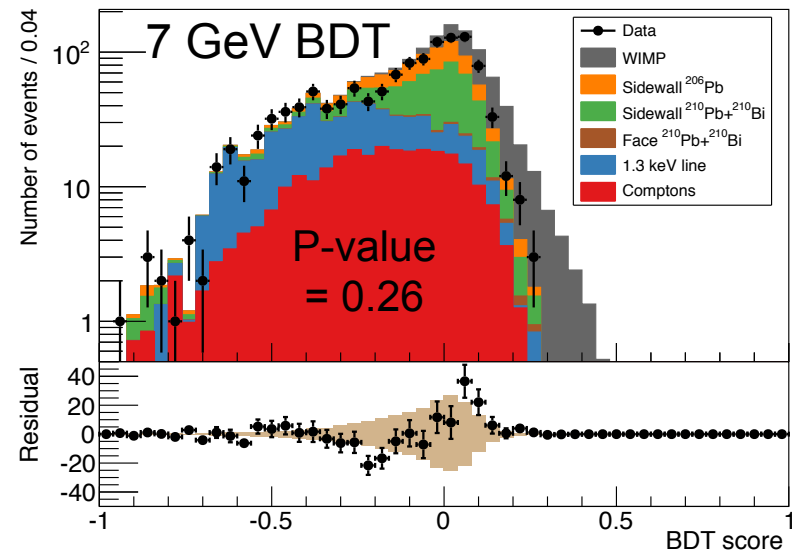
11 candidates seen, 6.2 +1.1 -0.8 expected

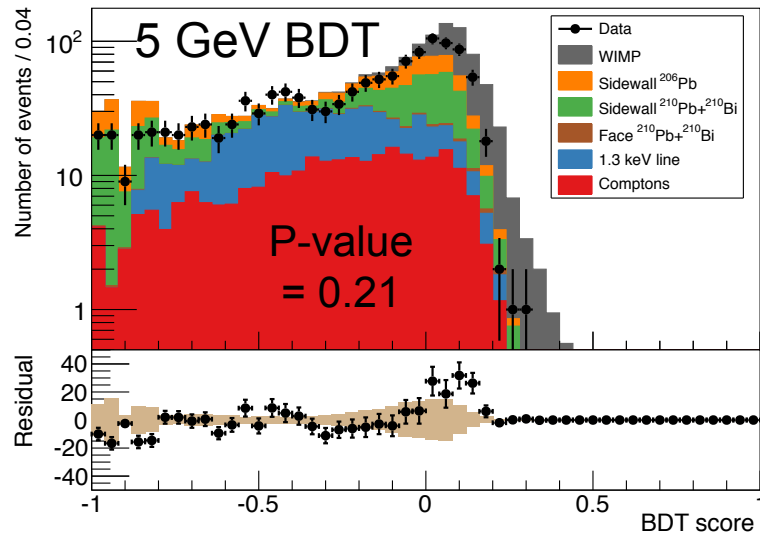# w/ 95% WIMP Confidence Intervals

11 candidates seen, 6.2 +1.1 -0.8 expected

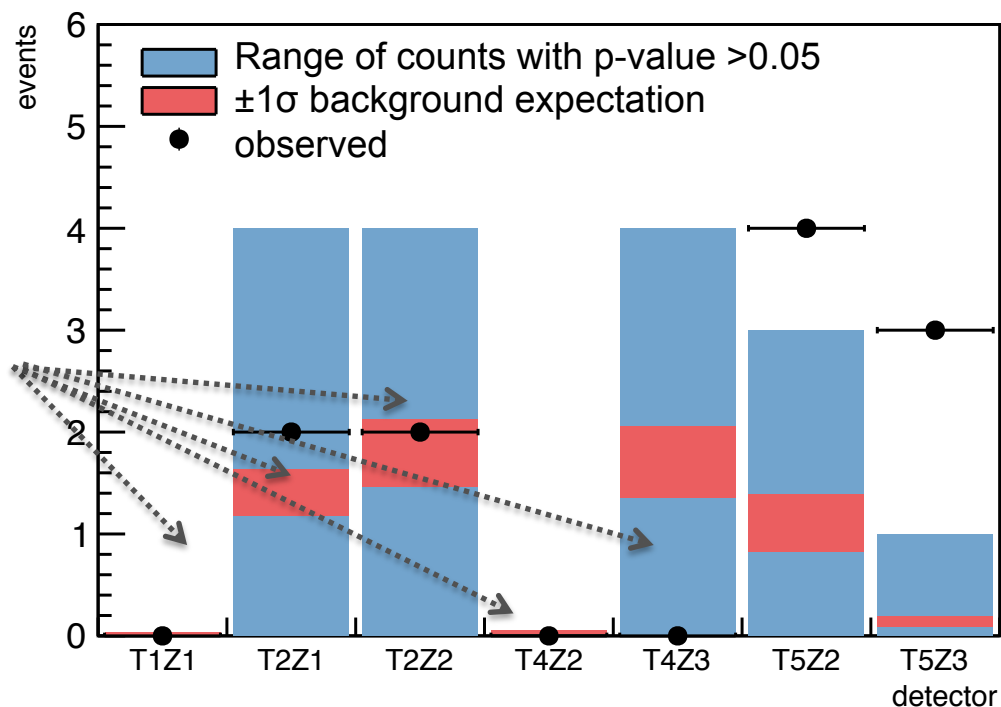# How model compares to data post-unblinding

WIMP model assumes:
$\sigma = 6 \times 10^{-42}$ cm^2

Post-unblinding discussion

Events generally high in quality
except lowest energy candidate, which looks like spurious noise.

Agreement with predicted background is good on most detectors

Legend:
- Range of counts with p-value >0.05
- ±1σ background expectation
- observed

Detectors (x-axis): T1Z1, T2Z1, T2Z2, T4Z2, T4Z3, T5Z2, T5Z3

y-axis: events (0 to 6)

x-axis label: detector
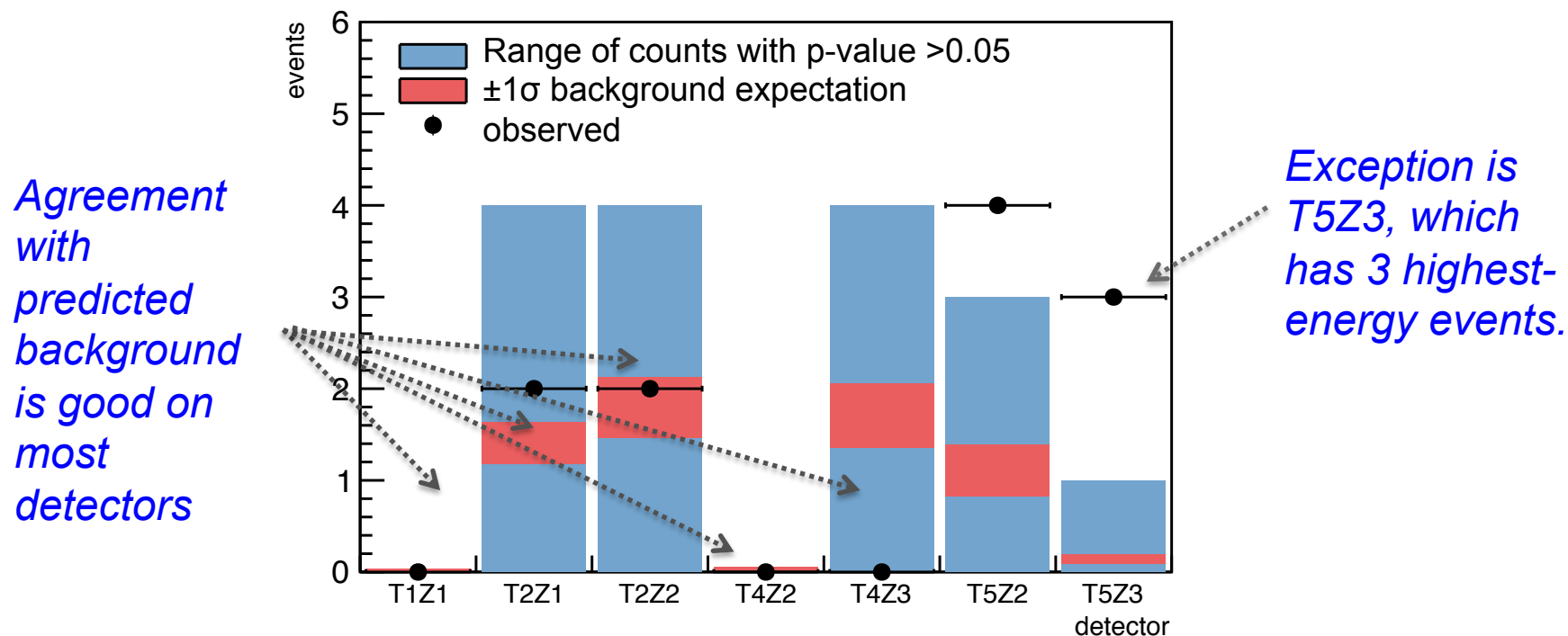
Post-unblinding discussion

Events generally high in quality
except lowest energy candidate, which looks like spurious noise.

*Agreement with predicted background is good on most detectors*

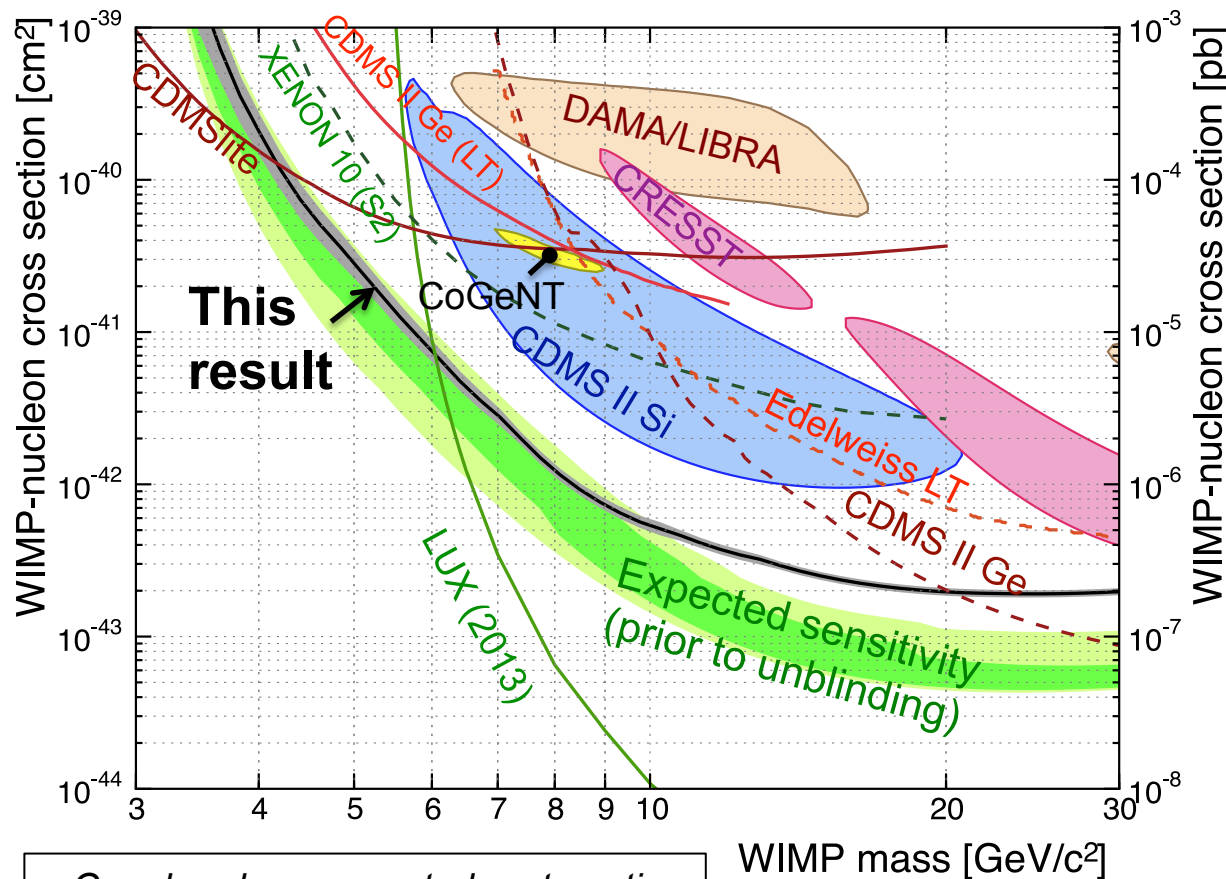*Exception is T5Z3, which has 3 highest-energy events.*

Probability for background to fluctuate up to 3 or more events is 0.0004 on T5Z3. This detector has a shorted ionization guard; at present it is unclear whether excess events are related, additional studies are ongoing

Post-unblinding discussion

Note: Detectors w/ higher thresholds (3-4 keV) have little expected leakage
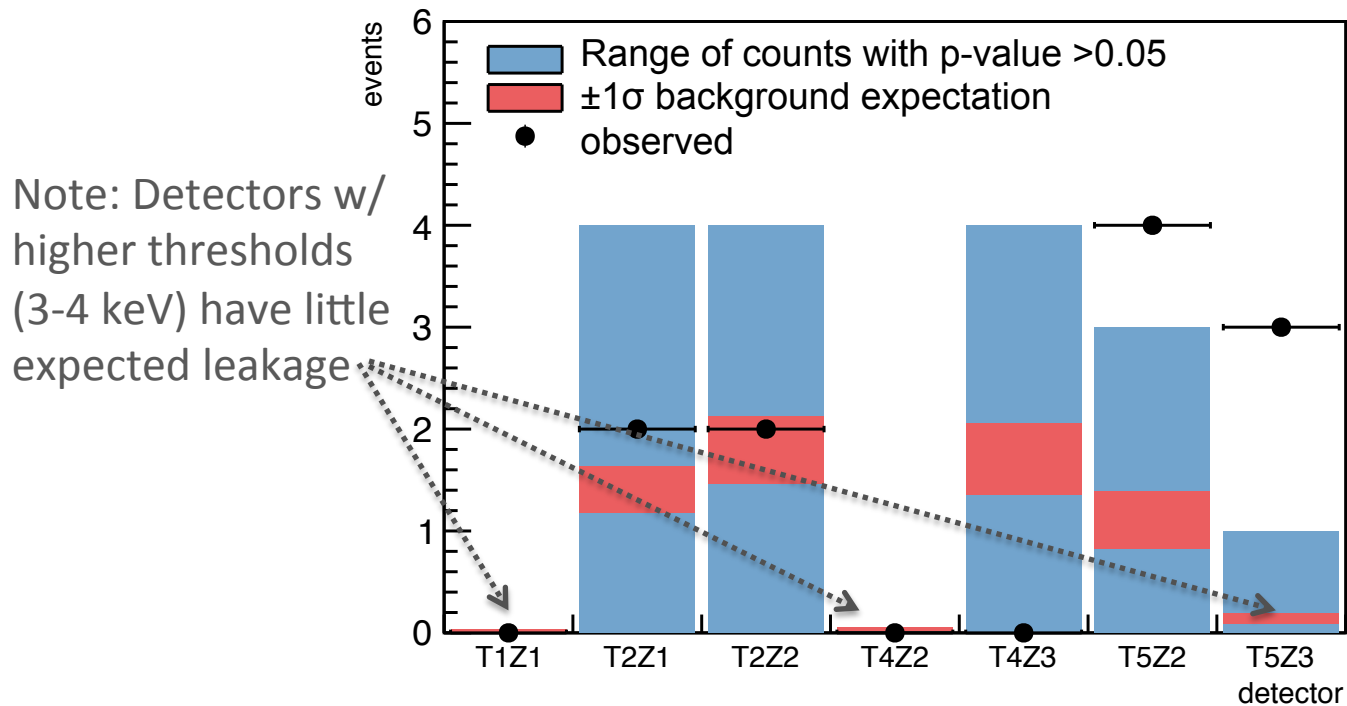
Spin-independent Scattering Constraints

90% C.L. optimal interval upper limit, no background subtraction, treating all observed (eleven) events as WIMP candidates

Gray bands: propagated systematic unc. from fiducial volume + nuclear recoil energy scale + trigger efficiency

- CoGeNT strongly disfavored in model-independent scenario

- CDMS II (Si) disfavored under assumption of standard halo model and A^2 coupling

- Explores new parameter space below 6 GeV/c^2

- Competitive constraint for Ge up to 20 GeV/c^2; dedicated HT analysis yet to come

- Disagreement between limit and sensitivity at high WIMP mass due to events on T5Z3.
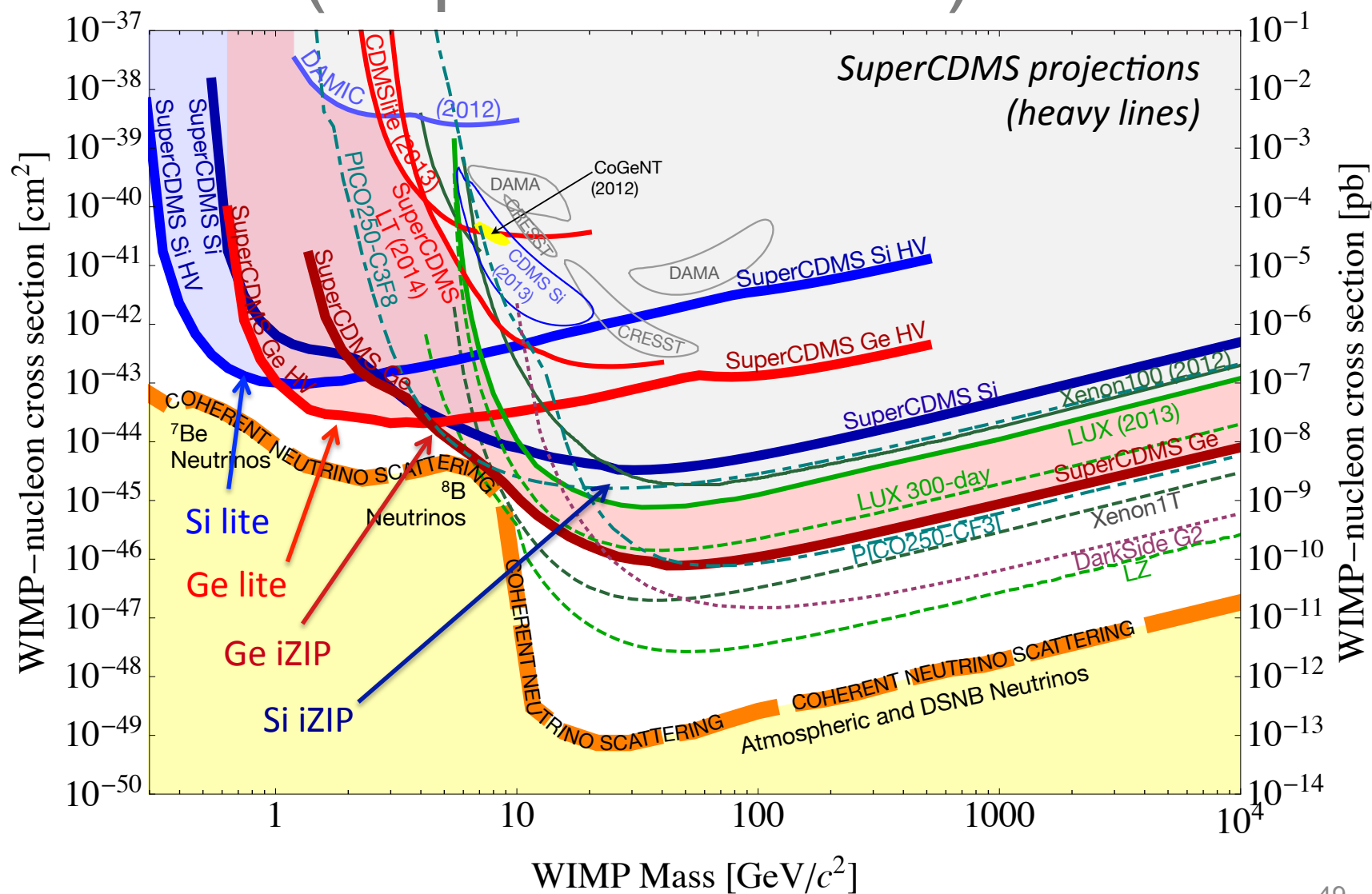
What about the CDMS II Si result?

Available parameter space is being tightly constrained by this result and others, but some select models still remain....
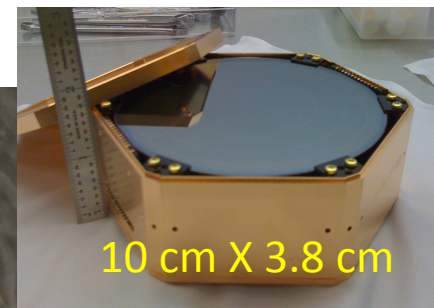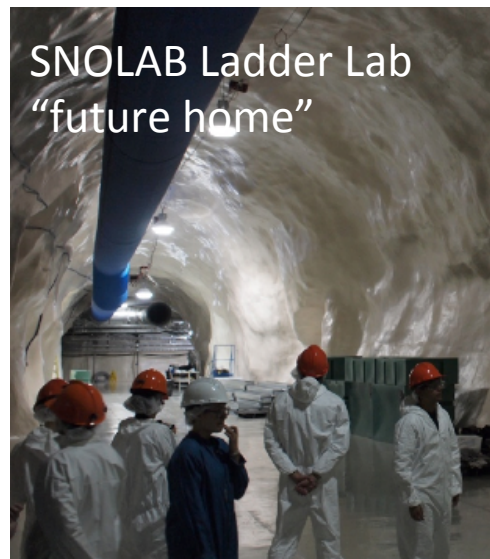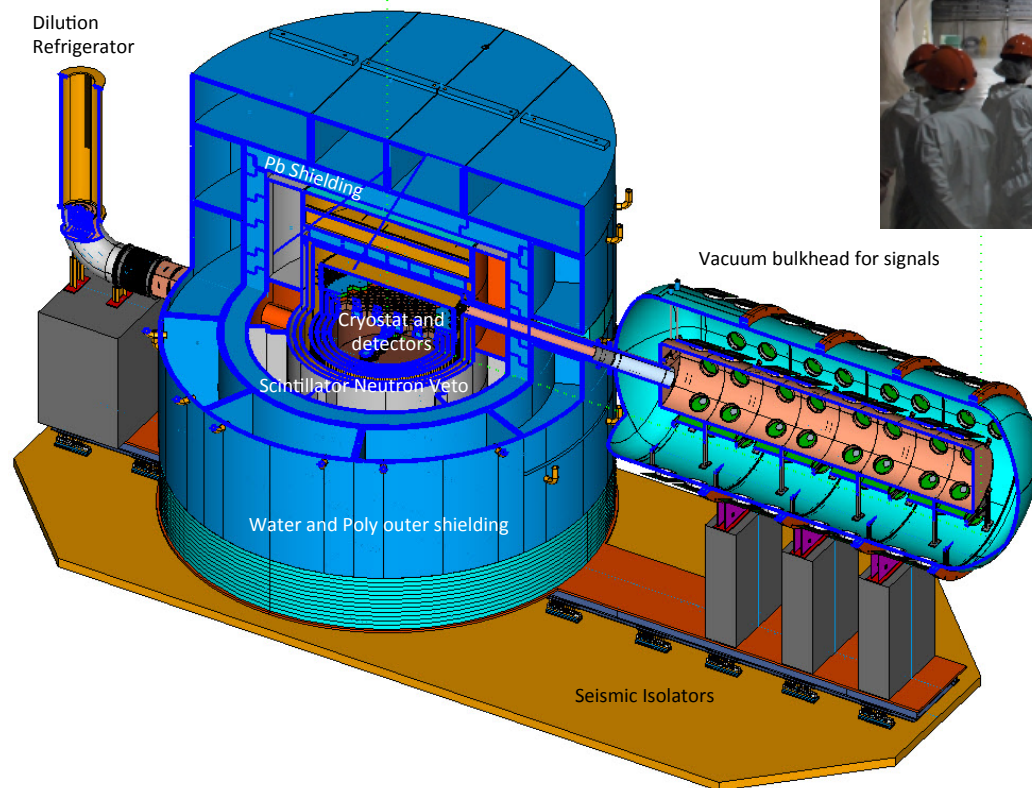
$$f_n/f_p = -0.7$$
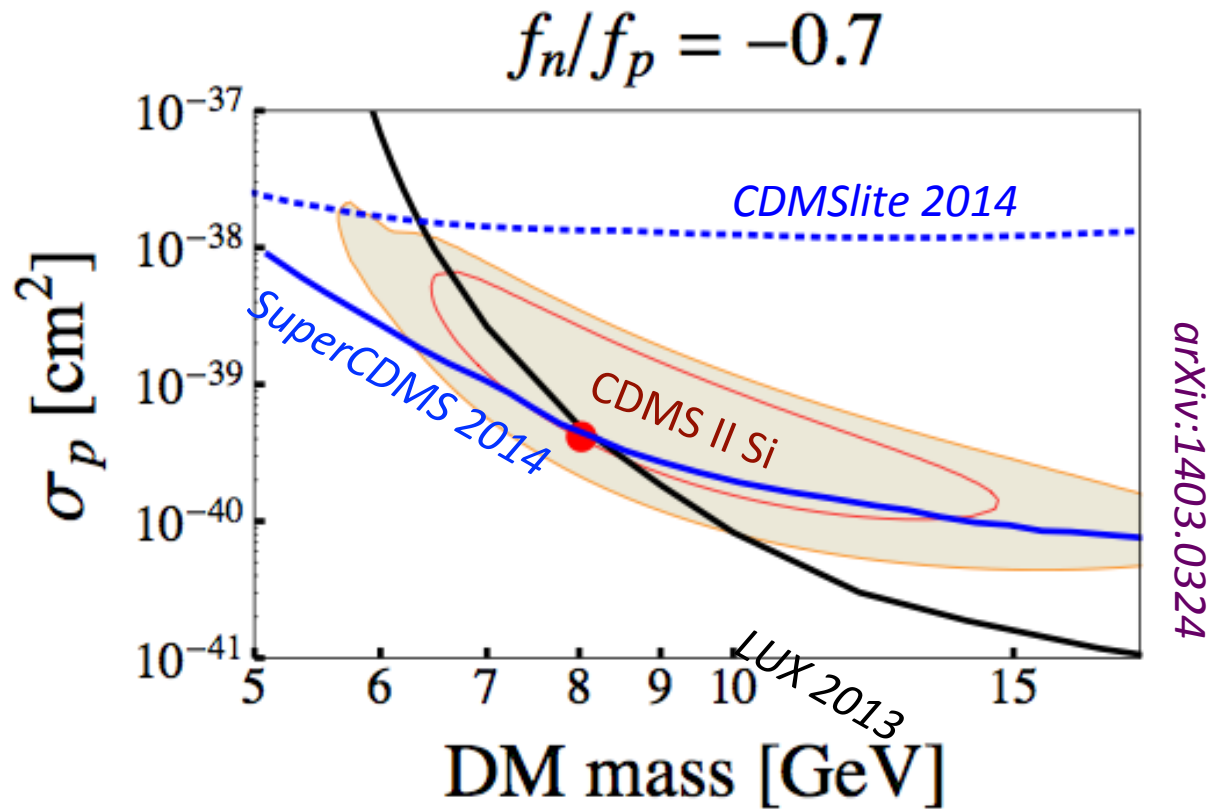
Example above from recent paper on isospin-violating dark matter
(w/ colored mediators)

The longer term picture (SuperCDMS G2)

WIMP Searches w/ SuperCDMS SNOLAB

SNOLAB Ladder Lab "future home"

10 cm X 3.8 cm

~100 kg of mixed Ge/Si payload, w/ 5% detectors configured in CDMSlite mode

Dilution Refrigerator

Pb Shielding

Cryostat and detectors

Scintillator Neutron Veto

Water and Poly outer shielding

Vacuum bulkhead for signals

Seismic Isolators

- Locate in North America's deepest underground lab
- Bigger iZIP detectors
- Cleaner shielding, w/ active neutron veto
- Upgraded electronics
- Room to expand to 400 kg

Summary

First result using background rejection capability of SuperCDMS!
arXiv: 1402.7137

7 iZIPs analyzed down to trigger threshold (1.6 keV$_{nr}$);
Exposure of 577 kg-days sets 90% C.L. upper limit to
WIMP-nucleon SI scattering, $\sigma = 1.2 \times 10^{-42} cm^2$, at 8 GeV/c^2

New phase space explored below 6 GeV/c^2

CoGeNT interpretation of WIMPs strongly disfavored in model-independent scenario; CDMS II (Si) region disfavored under standard halo model and A^2 coupling

SuperCDMS SNOLAB will have unprecedented reach in searches for low-mass WIMPs and complementary sensitivity in searches for high-mass WIMPs